Influences on continental margin development: a case study from the Santos Basin, South-eastern Brazil

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Influences on continental margin development: a case study from the Santos Basin, South-eastern Brazil

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Abstract

South Atlantic margins display significant variation in structural style along their length. An understanding of factors that influence this variation in structural style is a key component in any understanding of the evolution of the South Atlantic. The Santos basin is an obliquely rifted basin located offshore SE Brazil. Structures in the basin are thought to have been influenced by the reactivation of basement structures and/or fabrics during the onset of the Gondwana breakup. The onshore region adjacent to the Santos Basin offers the chance to test whether basement structures have played a significant role in influencing the initiation and development of syn-rift faults, dykes and fractures.

Field and remote sensing studies of the onshore region and on the conjugate margin in Africa show the strong geometric and temporal link between major 135Ma dyke swarms and the development of faults and fractures. 3 structural domains are defined, and correlated with lineament domains from the African margin. Faults, dykes and fractures within the lineament domains in SE Brazil share consistent orientations as large scale morphotectonic lineaments. Brittle structures show orientations and kinematics that are consistent with regional E-W oriented transtension. Little evidence of basement influence can be seen at outcrop scale, although it is speculated that larger scale structures may be reactivated.

Faults in the offshore basin share similar geometries to brittle structures onshore. As rifting progressed, and dyke intrusion ceased, NNE-SSW trending structures to the north of the basin ceased to be active, while N-S trending extensional faults continued to deform. N-S trending faults and fractures are also observed to cut dykes in the onshore region. The importance of understanding onshore geology when interpreting offshore basins is highlighted in this study, as is the need to integrate diverse datasets when trying to understand the complex influences on margin development.

Declaration

This thesis is submitted for the degree of Doctor of Philosophy at Durham University. This thesis is my own work except where stated in the text. No part of this thesis has been or is being submitted at this, or any other, university for a degree or any other qualification. This thesis does not exceed the word limit.

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1 Introduction

The geometry and structure of continental margins has been, since the early days of plate tectonic theory, thought to relate to the geometries of pre-existing crustal structures formed during past orogenic events (Dunbar and Sawyer, 1988; Wilson, 1966). The nature of this relationship is poorly understood, and a variety of other possible controls on passive margin orientation have been suggested (Burke and Dewey, 1973; Tommasi et al., 2009). Continental passive margins are often important hydrocarbon provinces, and therefore an understanding of their development and evolution is crucial in order to understand prospectivity in these regions.

The Santos basin is an obliquely rifted passive margin basin located offshore Rio de Janeiro, South-eastern Brazil. It was rifted during the formation of the Atlantic Ocean in the Early Cretaceous, with rifting accompanied by igneous intrusion and volcanics (Ponte and Asmus, 1978). Recent multi-billion barrel discoveries such as Tupi (now Lula) and Jupiter found in the syn-rift, pre-salt strata (Scotchman et al., 2010) highlight the economic importance of the basin, and the need to understand its tectonic evolution.

Structures in the basin are thought to be influenced by structures in the Ribeira belt, a Proterozoic mobile belt formed during the amalgamation of the supercontinent Gondwana (Unternehr et al., 1988). Onshore, rift-related brittle structures as well as those relating to more recent tectonic events, appear to trend parallel to Ribeira belt structures (Ponte and Asmus, 1978). The region, therefore, provides an ideal location to study the potential influences on the development of structures relating to the opening of the South Atlantic. Furthermore, an understanding of the processes which influence the development of the south Atlantic margin could potentially impact our understanding of passive margins and continental rifts worldwide.

The study is focussed on the conjugate south Atlantic margins of Brazil, Angola and Namibia. Lineament analysis was carried out across both of these margins in order to understand the large scale, 2-dimensional geometries of structures on the margins. The Brazilian margin was studied further, with fieldwork and offshore seismic data used to understand the timings, 3D geometries and kinematics of brittle faults and dykes, and their relationship with basement structures.

This thesis is presented as follows:-

Chapter 1: Introduction

A brief outline to the project, its rationale and its structure

Chapter 2: Regional geology

This chapter describes the geology of the study area, from the basement geology of the Brasiliano mobile belts in the area to the rift-related and post rift geology. An understanding of the basement geology is crucial when understanding the role it has played in influencing brittle structures, such as faults and dykes.

Chapter 3: Oblique tectonics and Continental rifting

This chapter deals with the theoretical background to the project. The beginning of chapter deals with oblique tectonics, transtension, and the role basement can play in the development of brittle structures. The latter part of the chapter also deals with the large scale tectonic processes involved in continental rifting and breakup, what is understood about hyperextension.

Chapter 4: Margin-scale Tectonic Geomorphology

Chapter 4 presents the results of a lineament analysis of the South American margin in SE Brazil. The chapter deals with the methodological considerations of both data processing and analysis; the link between lineaments and geological structure; and what this analysis tells me about rifting. Data from lineament analysis of southern Angola and northern Namibia is also correlated with the South American dataset, allowing correlations between syn-rift structural domains on either side of the Atlantic.

Chapter 5: Outcrop scale processes and relationships

This chapter presents the results of fieldwork on the Brazilian margin. In order to understand the relationship between basement structures and the development of brittle structures, measurements of faults, fractures, dykes and basement structures were collected from outcrops from across South-eastern Brazil. Field photographs and stereonets are used to present the field data, which is interpreted in terms of geometry and where possible, kinematics. Whether the margin is actually transtensional in origin is discussed, as are the regional implications of the results of the field based study.

Chapter 6: Santos Basin Architecture and Evolution

The evolution of the offshore basin is a key focus of this thesis. This chapter presents maps of horizons in the offshore basin, based on interpretation of 2D and 3D seismic data. Geometries and timings of faulting are discussed, as are the implications of this study to the development of the region.

Chapter 7: Discussion, conclusions, and future work

This chapter integrates the different datasets into a regional model for the evolution of the Santos basin. Issues with the various datasets used in the project are discussed, as is discussion of how my work sits in the context of other literature. Finally, the conclusions of the project are presented, together with recommendations for future work to test and expand the findings of this thesis.

Appendices

This chapter contains enlarged versions of the figures from the lineament analysis, field photographs, and offshore data analysis.

2 Regional geology

2.1 The study area

The study area for this thesis is located in the coastal region of south-eastern Brazil, in the Rio de Janeiro, São Paulo, Paraná, and Santa Catarina states. It comprises an area of approximately 200,000km^2, located between 42° and 49° west, and between 22° and 28° south (Fig. 2.1). The onshore region borders the Santos basin, an important hydrocarbon province. In Africa, the studied region covers southern Angola and northern Namibia, between 12° and 15° east, and 11° and 20° south (Fig. 2.1).

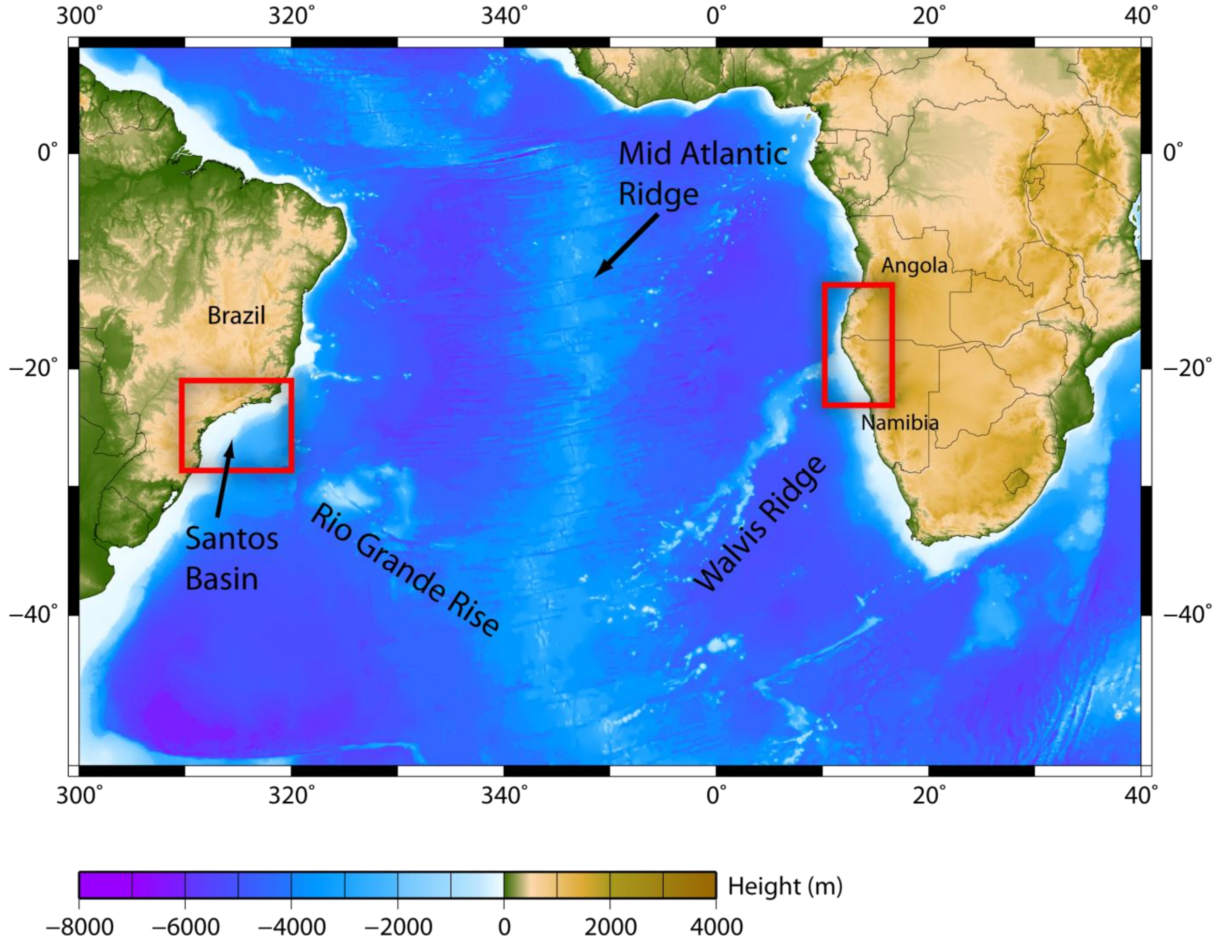


Figure 2.1 – Topographic and bathymetric map of the southern Atlantic Ocean. The approximate locations of the Brazilian and African study areas are highlighted with red boxes. The Walvis ridge and Rio Grande rise are thought to represent mantle plume tracks formed during rifting. The mid Atlantic ridge formed as the result of breakup of south Atlantic rifted basins. Transforms on the ridge highlight the east-west regional extension.

2.2 Regional Tectonics

South America and Africa were rifted during the Mesozoic breakup of Gondwana (Nurnberg and Muller, 1991). The location and timing of rifting is still debated, and appears to follow a complex timeframe (Fig. 2.2). In general, south Atlantic rifting began in the south of Gondwana (modern day southern Argentina and South Africa) during the Jurassic, and propagated northwards, with breakup complete by the upper Cretaceous (Rabinowitz and LaBrecque, 1979). The oldest ocean crust in the south is between 134 and 132Ma, whereas in the north it is approximately 112Ma in age (Moulin et al., 2010).

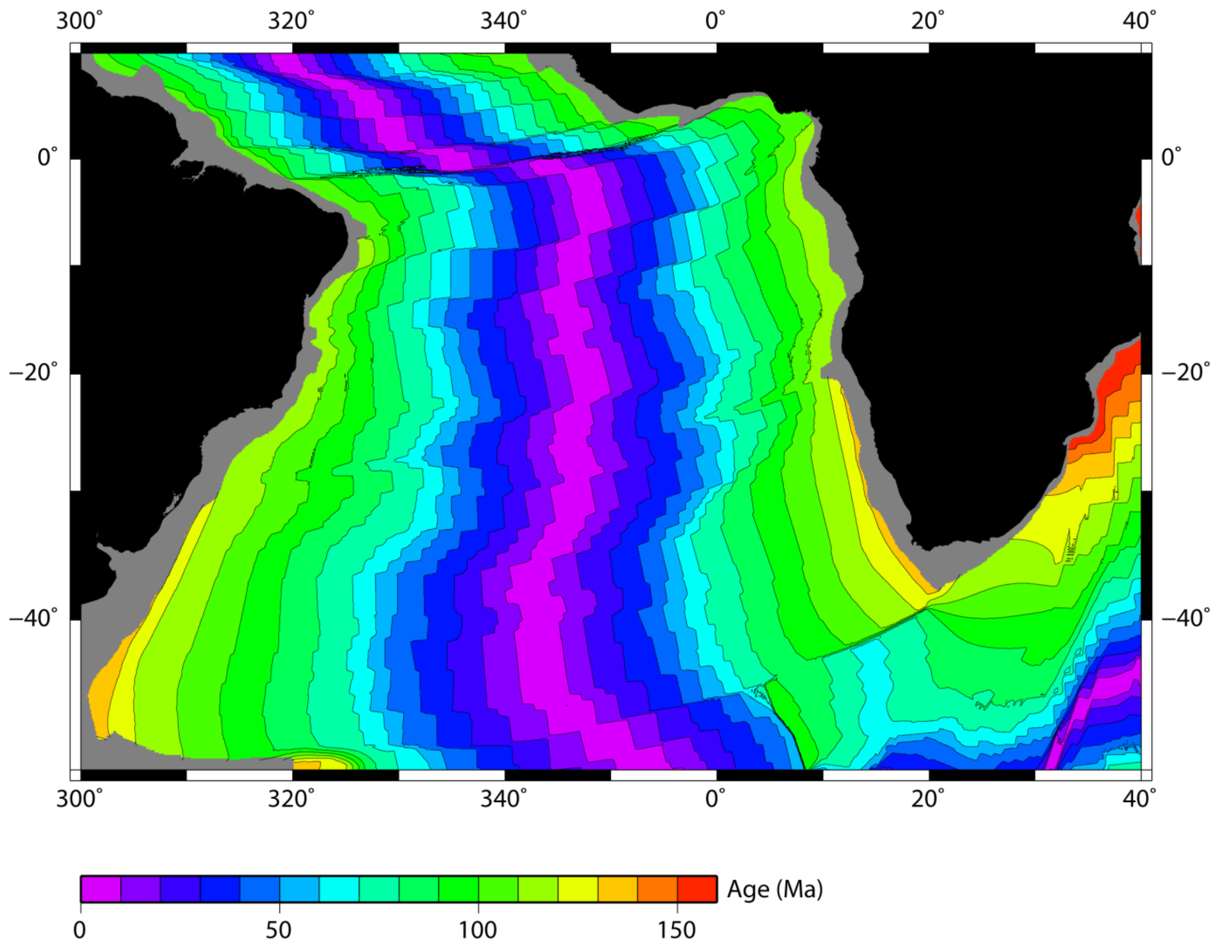


Figure 2.2 – Magnetic isochrons of the south Atlantic (data from Gplates software (Gurnis et al., 2011; Müller et al., 2008)). Isochrons are at 10Ma intervals. Isochrons at the continental margin are oldest in the south and progressively younger northwards. These ages indicate the Santos basin (Fig. 2.5) experienced breakup between 110 and 120 Ma

On a smaller scale, the spatial and temporal pattern of rifting is more complex, with several intracontinental basins developing diachronously north of the Walvis ridge (a hot-spot track located approximately at 33° S) (Davison, 1999). As rifting continued, these basins continued to extend, before linking during the Early Cretaceous (Neocomian), and forming wide basins separated by local basement highs (Davison, 2007). During this period, the south Atlantic experienced large scale igneous activity, leading to flood basalt extrusion in the Paraná – Etendeka province and the intrusion of large tholeiitic dyke swarms (Hawkesworth et al., 2000).

The Santos basin is found offshore Rio de Janeiro, São Paulo, Paraná and Santa Catarina states. The basin is approximately 600km wide (Davison, 1997), and began to rift during the Neocomian. Breakup was complete by the late Cretaceous. Sediments in the basin reach 5.3km in thickness. The basin is bordered to the north by the Cabo Frio high, and to the south by the Florianopolis fracture zone. The Pelotas basin; a volcanic rifted basin, lies to the south of the Florianopolis fracture zone, whereas the non-volcanic Campos basin lies to the north of the Cabo Frio high.

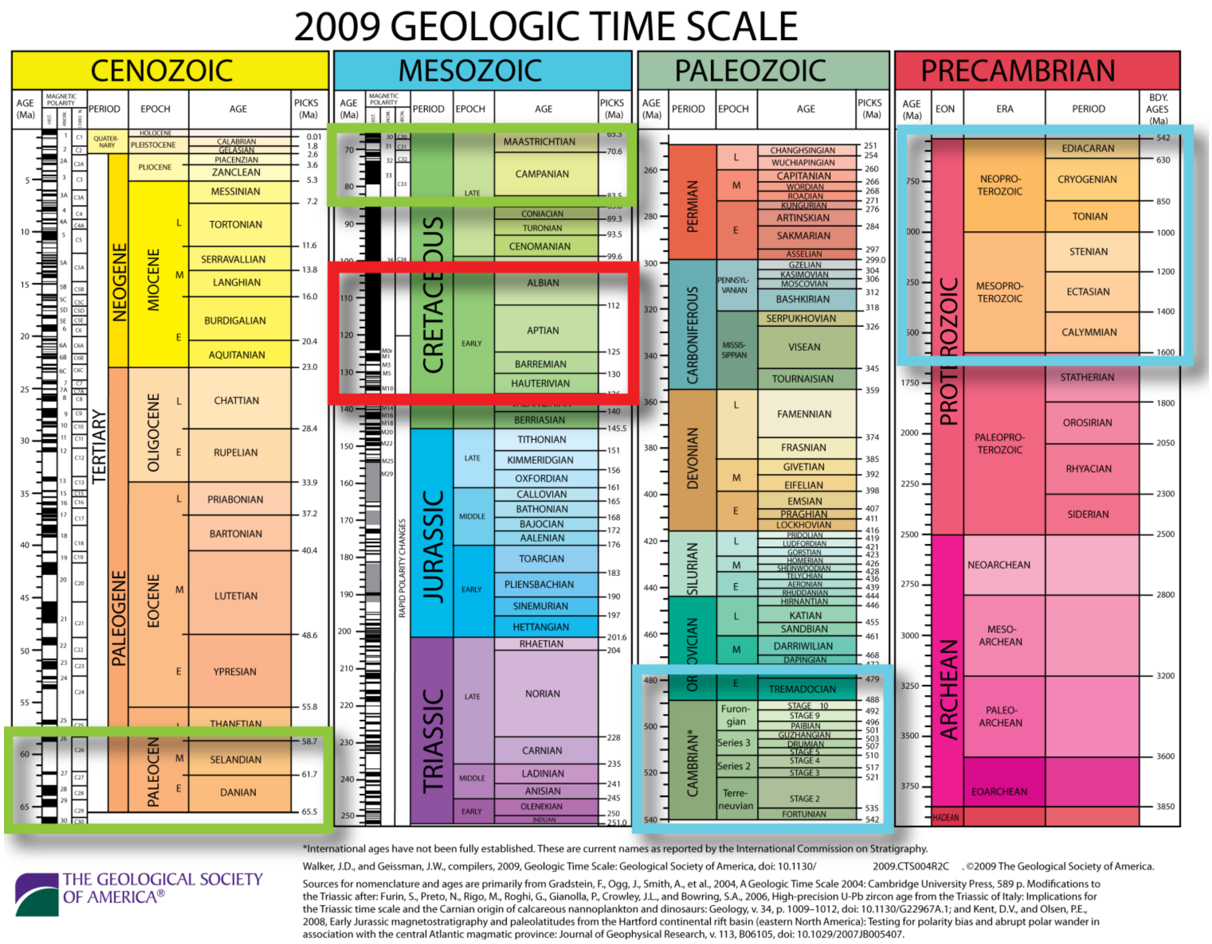


Figure 2.3 – The geologic time scale (Walker and Geissman, 2009). The most relevant periods to this study are the pan-African orogeny (blue), during which the Ribeira and Kaoko belts were formed, the Neocomian period of the Late Cretaceous (red), during which the Atlantic rift was formed, and the Late Cretaceous – Early Cenozoic (green), when the Serra do Mar (SE Brazil) was uplifted and onshore sedimentary basins developed.

Onshore in Brazil, large regional uplift episodes have occurred post-breakup (Gallagher et al., 1994), leading to the formation of the Serra do Mar – a coastal mountain belt. This uplift was accompanied by alkaline magmatism, and the formation of a series of sedimentary basins (Figure 2.13) known as the ‘Cenozoic rift system of southeastern Brazil’ (Zalán and Oliveira, 2005). Neotectonic activity in the area is documented, and thought to be caused by far-field compressive stresses related to the subduction of the Nazca plate beneath the South American Plate during the Andean Orogeny (Cobbold et al., 2001).

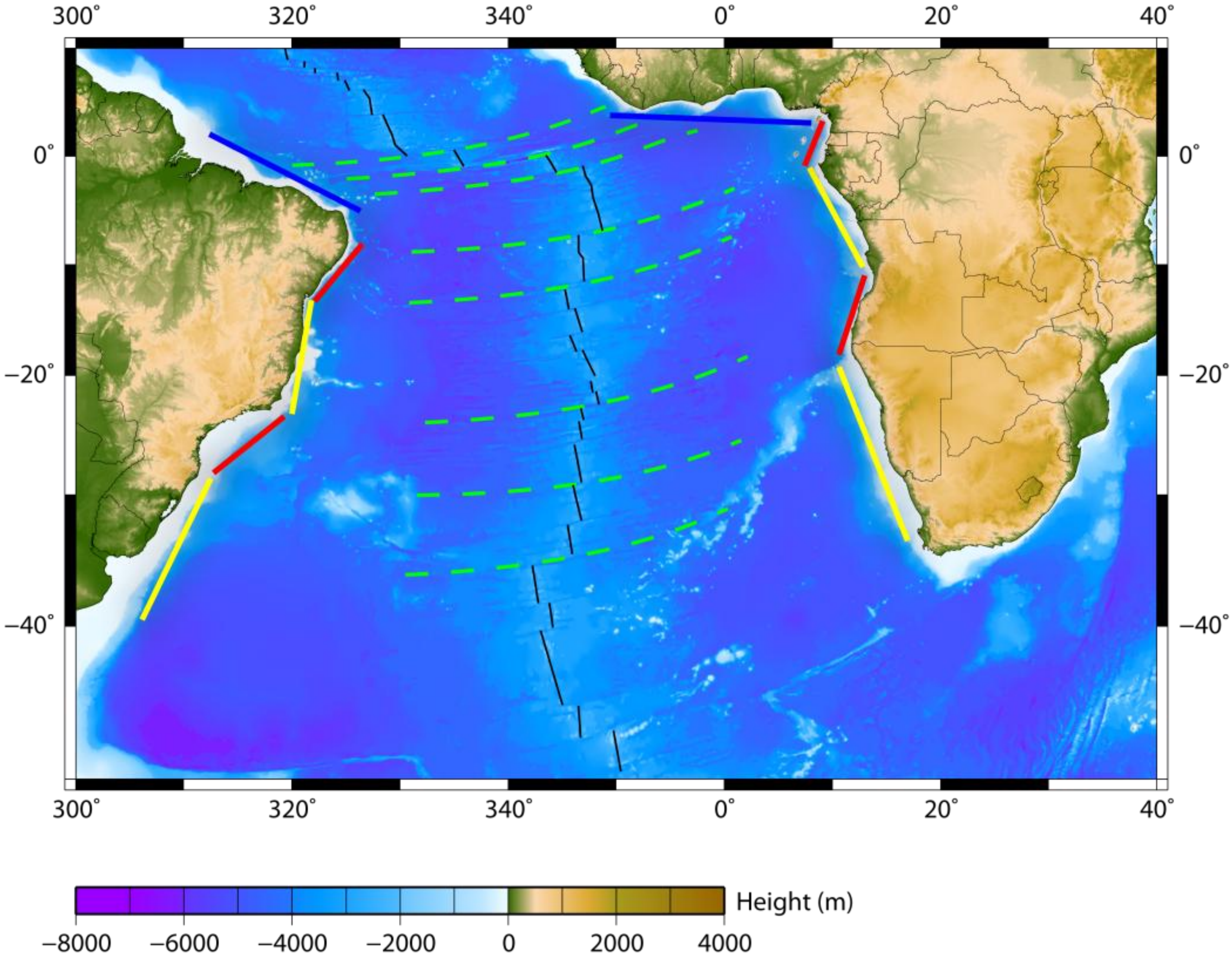


Figure 2.4 Orthogonal (yellow), oblique (red) and transform (blue) margins of the south Atlantic. Note the transforms offsetting the mid-Atlantic ridge (black). Some major transforms are highlighted with green dashed lines. These form perpendicular to ocean spreading and are used to track the extension directions.

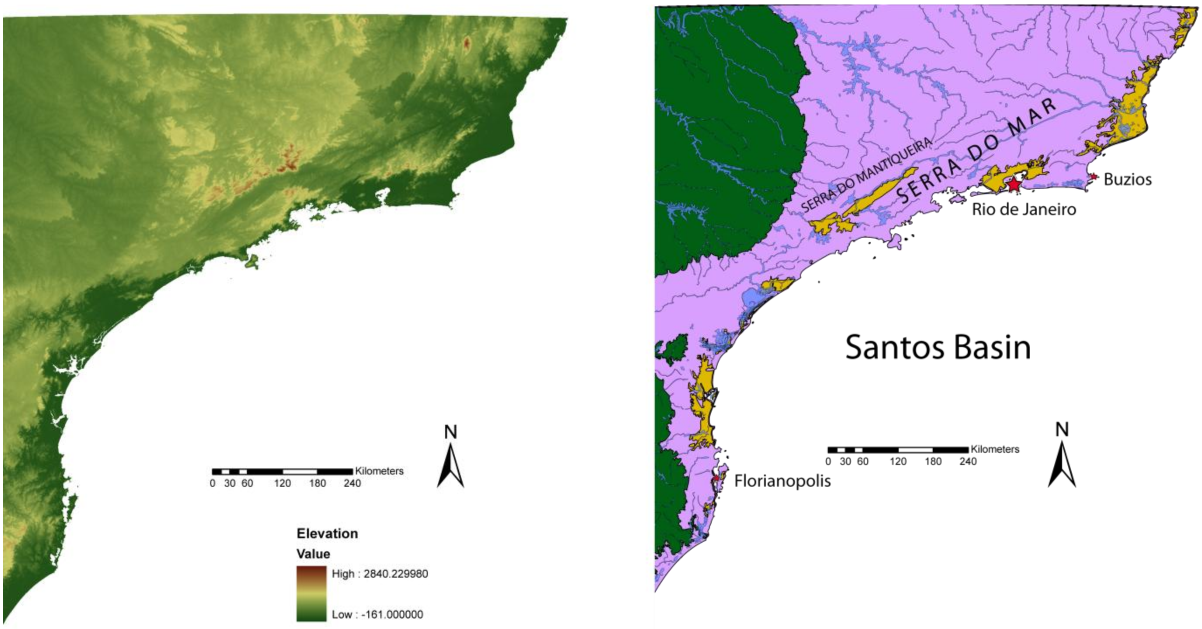


Figure 2.5 – Topography and simplified geology of the study area. The topographic map clearly shows the NE-SW trending mountain belts and basins (marked in yellow) formed during post-rift uplift. The geology map shows the Paraná basin marked in green, whilst the majority of basement – Brasiliano and older crystalline rocks, are marked in pink. Note the strong coast-parallel drainage patterns. The onshore study area extends between Buzios to the northeast, and Florianopolis to the southwest. Geology modified from Davison et al (1999).

2.3 Basement Geology

2.3.1 The Ribeira belt

The Ribeira belt is a Neoproterozoic orogenic belt, which formed during the amalgamation of Gondwana (Hackspacher et al., 2001). In west Gondwana, now modern day south America and Africa, these 'mobile belts' coalesced into cratons and cratonic fragments during the period known as the Brasiliano or Pan-African orogeny (Windley, 1984). The Ribeira Belt forms a part of the Mantiqueira province, a system of mobile belts associated with the Brasiliano orogeny (de Almeida et al., 1981).

The Ribeira belt is a NE-SW trending belt which separates the Congo and São Francisco cratons (Pedrosa-Soares et al., 1998). It is exposed mainly in the Rio de Janeiro, São Paulo and Paraná states, and was formed during subduction and continental collision related to the closure of the Adamastor Ocean, between approximately 790 and 480 Ma (Heilbron and Machado, 2003). The belt is roughly parallel to the modern day coastline, and is thought to extend offshore to underlie parts of the Santos basin (Schmitt et al., 2008). To the north, the belt curves to a more N-S orientation. This part of the belt is called the Araçuaí belt (Fig. 2.6) and runs coast-parallel, adjacent to the Campos basin. Reactivation of the Araçuaí belt is thought to play a large role in the early structural evolution of the Campos basin (Fetter, 2009; Ponte and Asmus, 1978). To the south, the Ribeira belt is bordered by the Luis Alves craton, a small cratonic fragment between the Ribeira belt, and the Dom Feliciano belt to the south (Brito Neves and Cordani, 1991; Cordani et al., 2003a; Trompette, 1997) (Figures 2.6 and 2.7)

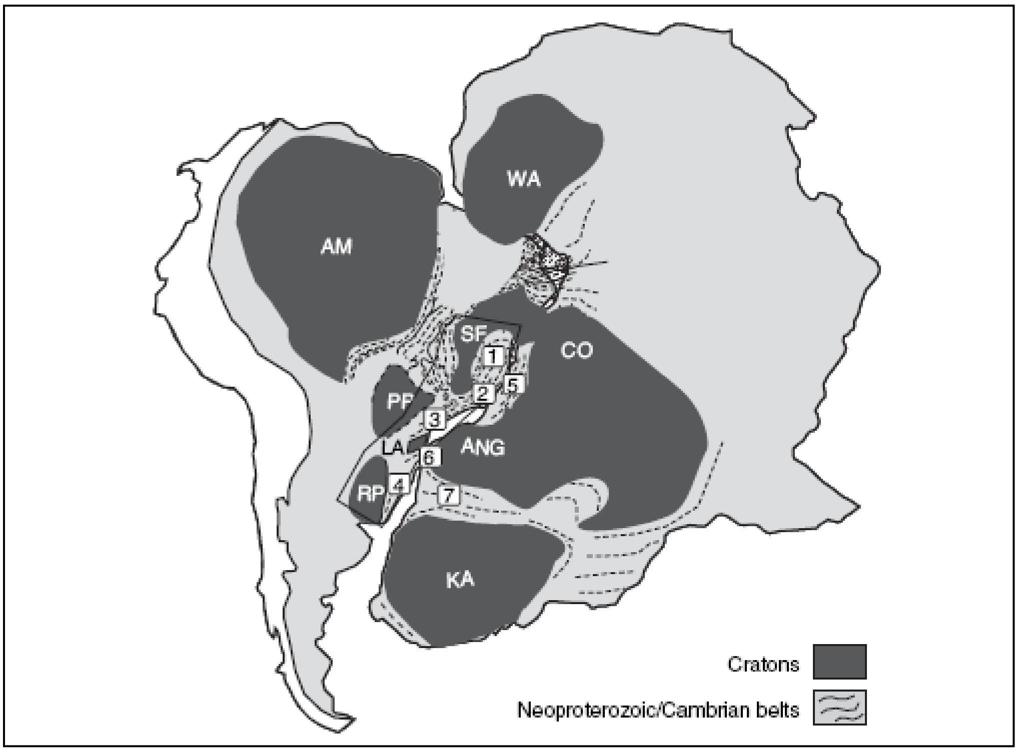


Figure 2.6 - Generalised Geology of western Gondwana from Heilbron, et al. 2008 (modified therein from Trompette, 2008). The Ribeira belt is represented by numbers 2 and 3 in the image. The Kaoko belt is number 6. The Araçuaí Belt is number 1. SF = São Francisco Craton, LA = Luis Alves craton, ANG = Angola craton, CO = Congo Craton

The Ribeira belt formed during regional dextral transpression in response to east-west compression (Ebert and Hasui, 1998). During transpression, a series of terranes, or domains, were accreted, (Schmitt et al., 2008). Each of these terranes represents basement and cover sequences of continental and oceanic origin formed during the opening and closure of the Adamastor ocean, which itself was created during the breakup of the supercontinent Rodinia at approximately 1Ga (Fuck et al., 2008; Trompette, 1997). These terranes are now separated by large, steeply dipping, NE-SW trending crustal shear zones (Fig. 2.7) (Trouw et al., 2000). Due to the complex nature of the collision, multiple deformation events are observable in each terrane (Fig. 2.8). The main terranes of the Ribeira belt are described below, from west to east, followed by the Luis Alves Craton, the Dom Feliciano belt, and the Florianopolis Batholith (Fig. 2.7)

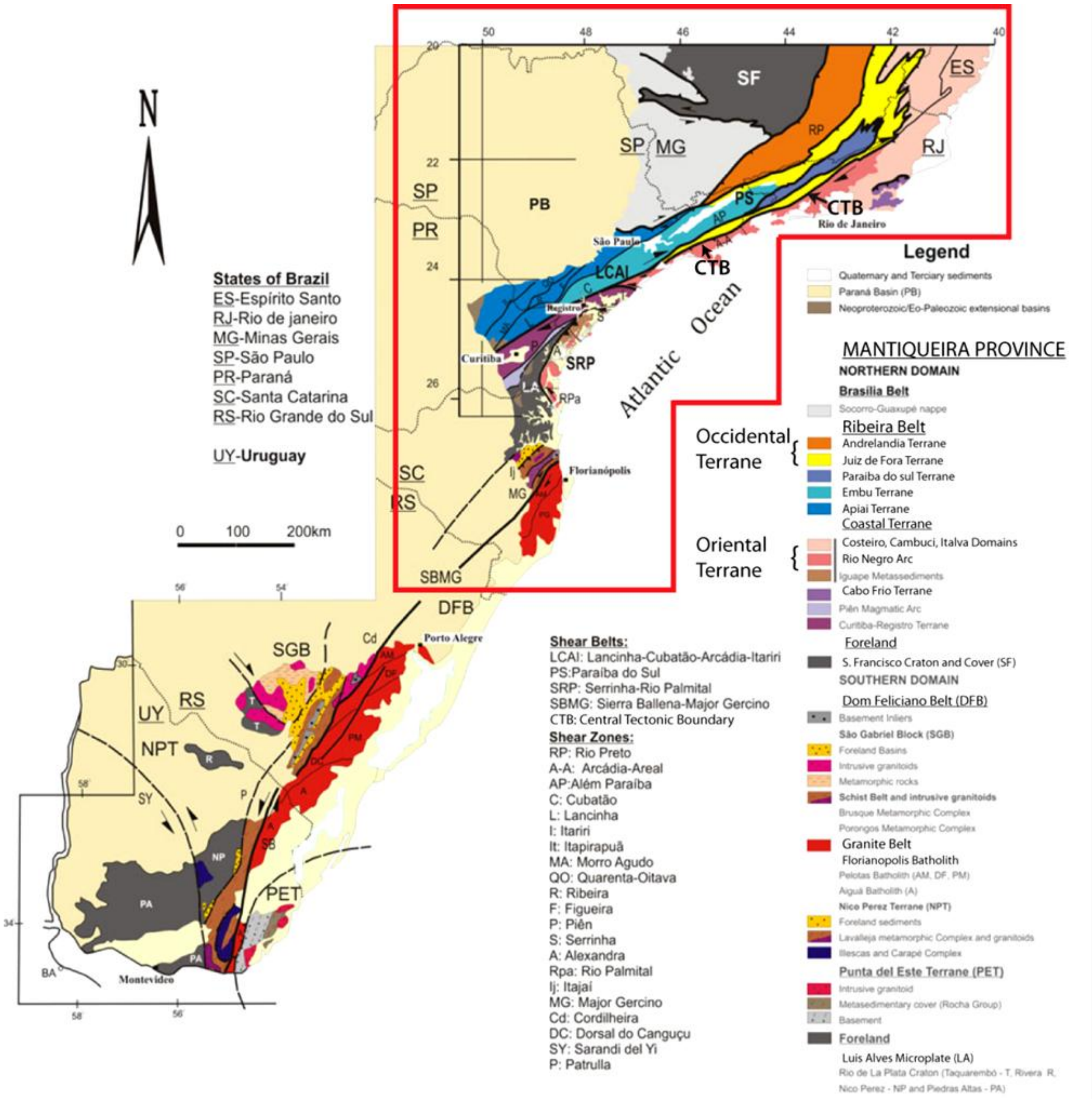


Figure 2.7 – Generalised geology of the Ribeira and Dom Feliciano belts, showing major terranes, modified from Passarelli et al, (2011). The red box marks the onshore study area. Note the strong NE-SW trend of the Ribeira belt, in contrast with the more NNE-SSW trending Dom Feliciano belt. The Central tectonic boundary has been marked on the map, as it forms an important crustal scale structure separating the Occidental and Oriental terranes.

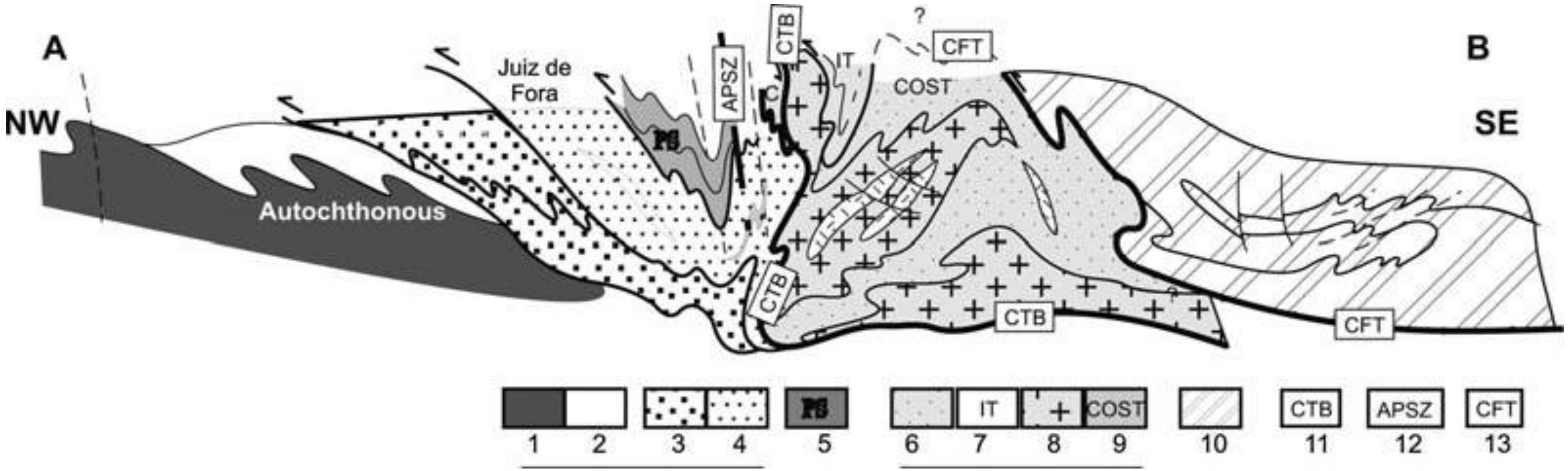


Figure 2.8 – Generalised cross section through the Ribeira Belt (Heilbron et al., 2008). 1-2 – Autochthonous Domain; 3-4 – Occidental terrane (Juiz de Fora and Andrelândia complexes respectively); 5 – Paraiba do sul Klippe; 6-9 – Oriental Terrane; 10 – Cabo Frio Terrane; 11 – Central Tectonic Boundary; 11-12 – Other major shear zones. The complex structure is the result of a number of deformation events, with some major structures such as the CTB significantly folded.

2.3.1.1 Terranes of the Ribeira Belt

2.3.1.1.1 Curitiba Terrane

The Curitiba terrane consists of Paleoproterozoic orthogneisses (and granulites, representing passive margin basement rocks, and metasedimentary rocks representing their cover sequences (Fig. 2.7). The main metamorphic episode is estimated to have occurred around 600Ma (Heilbron et al., 2008). It is separated from the Luis Alves craton by the NE-SW trending Pien Shear zone, and from the Embu and Apiaí terranes by the 490-500Ma (K-Ar), NE-SW trending, dextral transpressional Cubatão shear zone (Passarelli et al., 2011).

2.3.1.1.2 Apiaí terrane

The Apiaí terrane is located in the far west of the Ribeira belt (Fig. 2.7). It is thought to have been a passive margin and magmatic arc which formed at the edge of the Paranapanema craton (which is now covered by Paraná basin sediments) (Hackspacher et al., 2008; Leite et al., 2007). The terrane trends NE-SW and consists of metamorphosed Mesoproterozoic marine sediments, and oceanic basement, consisting of gneisses and migmatites (da C. Campanha and Sadowski, 1999). Units are separated by NE-SW trending thrusts and dextral transpressional shear zones, which form the "Cubatão megafault system" (da C. Campanha and Sadowski, 1999). The terrane has been intruded by both syn-and post-collisional granitoids, dated at 600-610Ma, and 564±8Ma respectively (dated using U-Pb from zircons) (Janasi et al., 2001; Leite et al., 2007)

2.3.1.1.3 Embu terrane

The Embu terrane forms a long belt of supracrustal and basement rocks accreted to the Ribeira belt approximately at 790Ma (from U-Pb dating of zircons) (Fig 2.7). It consists of gneisses metamorphosed to amphibolites facies, and supracrustal rocks, metamorphosed to amphibolites facies during the same event (da Silva et al., 2005a). The terrane trends NE-SW, and is bounded by two major shear zones, the Cubatão shear zone to the south, and the Taxaquara shear zone to the north. Both of these shear zones formed during dextral transpression (Passarelli et al., 2011). Pre-collisional magmatism occurred at 810Ma (protolith age from U-Pb dating of zircons), recorded in tonalitic gneisses. The terrane was further intruded by syn-collisional plutons around 650-580Ma (U-Pb from zircons) (da Silva et al., 2005a).

2.3.1.1.4 Occidental terrane

The Occidental (western) terrane represents the reworked passive margin of the Sao Francisco craton. It is largely composed of Meso- to Neo-proterozoic aged amphibolite to granulite facies metasediments, and Palaeoproterozoic and older basement, consisting of granulites and migmatites (Heilbron et al., 1998; Heilbron et al., 2008). This terrane is split further into the Andrelândia and Juiz de Fora thrust sheets (Fig. 2.7). The southern boundary of the Occidental terrane is called the Central Tectonic Boundary, and consists of a large scale Neoproterozoic dextral transpressive structure known as the Paraiba do Sul shear zone which separates the Occidental and Oriental terranes (Karniol et al., 2008; Schmitt et al., 2004). This shear zone is considered by some authors to be part of the same 'shear belt' as the Cubatão shear zone, which forms the southern boundary of the Embu terrane (da C. Campanha and Sadowski, 1999; Passarelli et al., 2011)

2.3.1.1.5 Andrelândia complex

The Andrelândia complex is the northernmost thrust sheet in the Occidental terrane. It formed on the passive margin of the São Francisco continent. It overthrusts an 'autochthonous domain' consisting of Archaean basement gneisses and greenschist to amphibolite facies metasediments (Heilbron et al., 2010). The Andrelândia complex itself consists largely of 900Ma metasediments metamorphosed to amphibolite facies at approximately 600Ma (Sm-Nd) (Paciullo et al., 2008). These sediments were thrust northwards over the passive margin. The complex was folded into large, NE-SW trending tight to isoclinal folds during thrusting (Heilbron et al., 2010).

2.3.1.1.6 Juiz de Fora complex

The Juiz de Fora complex is located in the southern part of the Occidental terrane. It is thought to represent the Palaeoproterozoic oceanic basement and sediments of the Adamastor ocean, thrust northwards over the Andrelândia complex during the amalgamation of Gondwana. The complex consists of granulite facies rocks in several thrust slices, separated by mylonites (Heilbron et al., 1998). Similarly to the Andrelândia complex, these slices trend NE-SW.

2.3.1.1.7 The Central Tectonic Boundary

The central tectonic boundary, or CTB, separates the Oriental and Occidental terranes (Almeida et al., 1998). It is considered to be a major boundary between rocks formed on the São Francisco plate, and terranes that have been accreted to it. It trends NE-SW, and its onshore trace is approximately 300km long (Heilbron and Machado, 2003). The dip of the CTB varies along its length. Towards the south, the shear zone dips towards the northwest. Further north, the CTB is folded, and dips shallowly to the southeast (Tupinambá et al., 2007). The CTB consists largely of high temperature mylonites with metasedimentary protoliths. Some granulites are also present (Almeida et al., 1998). The CTB is thought to have evolved from top to WNW thrusting to dextral transpressive shearing between 640 and 480Ma

2.3.1.1.8 Paraiba do Sul Klippe

The Paraiba do Sul Klippe is a NE-SW trending synformal structure consisting mainly of supracrustal rocks, particularly metasediments and metavolcanics, metamorphosed to amphibolites facies (Heilbron et al., 2008). It is cut by NE-SW trending shear zones, which dip to the south on the northern limb of the structure, and to the north on the southern limb, forming a ‘fan like’ structure (Dehler et al., 2006). This structure was formed between 605 -570 Ma (Heilbron et al., 2008). A major dextral shear zone – the Paraiba do Sul shear zone, separates this terrane from the Embu terrane to the north (Passarelli et al., 2011). Internally, the terrane contains a large number of dextral transpressional shear zones, and some extensional structures, concurrent with transpressional deformation have also been identified (Dehler et al., 2006).

2.3.1.1.9 Oriental terrane

The Oriental terrane is found in the eastern region of the Ribeira belt, and trends NE-SW through Rio de Janeiro and São Paulo states. The terrane consists mainly of high grade metamorphic rocks (amphibolite-granulite facies gneisses) interlayered with metasediments and granitoids of Neoproterozoic or younger age (Heilbron and Machado, 2003). It docked with the Occidental terrane between 590 and 550Ma (Heilbron et al., 2008). The terrane is split into 3 main regions, separated by top-to-the-north thrusts. These are: the Cambuci domain, consisting of metasediments formed in a forearc setting; the Italva Domain, representing continental shelf basement and sediments; and the Costeiro Domain, which represents basement rocks of the Rio Negro Magmatic Arc (Heilbron et al., 2008).

2.3.1.1.10 Rio Negro magmatic arc (Costeiro domain)

The Rio Negro Magmatic arc forms a large part of the southern Oriental terrane, and represents arc rocks formed above a subduction zone, that were then accreted onto the rest of the Ribeira belt. The terrane consists largely of orthogneisses, together with pelitic paragneisses, which formed as arc crust and sediments in two stages, the first at approx. 790Ma, and the second between 635 and 620Ma. The arc collided with the Ribeira belt between 580 and 550Ma (Heilbron et al., 2008). The Rio Negro arc is separated from the Juiz de Fora domain of the Occidental terrane by the CTB. Its relationship with the rest of the Oriental terrane is less clear, as much of the boundary is located in the low-lying, poorly exposed coastal regions of Rio de Janeiro and São Paulo states, and is covered in younger, post-rift sediment.

2.3.1.1.11 Cabo Frio Terrane

The Cabo Frio terrane is the easternmost of the Ribeira belt terranes, and is thought by some to not represent a contiguous part of the Ribeira belt, and instead be related more to the African margin (Schmitt et al., 2008). Whilst its boundary with the Oriental terrane trends NE-SW, orientations of structures within the terrane are more diverse than those in the rest of the Ribeira belt (Schmitt et al., 2004). The terrane consists of highly deformed basement and cover sequences composed of felsic orthogneisses and metabasic paragneisses thought to represent the passive margin of a continent to the east of the Rio Negro arc. The basement is thought to be metamorphosed felsic igneous rocks, which crystallised between 2000 and 1950Ma, based on U-Pb ages of zircons (Schmitt et al., 2004). Mafic igneous rocks are also present, as lenses or boudins of amphibolite in basement rocks, and are thought to have crystallised contemporaneously with the felsic rocks (Schmitt et al., 2004). The cover sequences are typically lower grade metasediments, metamorphosed to amphibolites facies. The cover sequences range between 1000 and 600Ma in age, based on U-Pb dating of detrital zircons (Schmitt et al., 2004) The Cabo Frio terrane collided with the rest of the Ribeira belt, during the last stages of the Brasiliano orogen in the Cambrian. The Cabo Frio terrane was thrust northwestwards over the Oriental terrane on a NE-SW trending thrust (Schmitt et al., 2008). Due to the apparent along-strike relationship, similarity in geology and age of the Cabo Frio and Curitiba terranes, Schmitt et al (2008) also suggest that the Cabo Frio terrane may be continuous with the Curitiba terrane, implying that the two are linked under the Santos basin.

2.3.1.2 Luis Alves craton

The Luis Alves craton crops out to the south of the Ribeira belt, in the Santa Catarina and Paraná states. It is a cratonic fragment of Paleoproterozoic age (Cordani et al., 2003b). The Luis Alves craton represents a microcontinent accreted between the Ribeira belt and the Dom Feliciano orogenic belts. Its basement geology consists of gneisses and mica schists, formed between 2350 and 2310Ma, based on U-Pb ages of zircons (Hartmann et al., 2000), with late stage 2010Ma leucogranites (Heilbron et al., 2008)

2.3.1.3 Dom Feliciano Belt

The Dom Feliciano belt is another pan-African orogenic belt, located south of the Luis Alves craton. Similarly to the Ribeira belt, it formed by terrane accretion during Gondwana amalgamation. The Dom Feliciano belt is thought to represent the eastern passive margin of the Adamastor Ocean, which closed during the Brasiliano orogeny. It is correlated with the southern part of the Kaoko belt in Namibia (Gray et al., 2008). Structures in the belt trend approximately NNW-SSE to NW-SE. The belt extends southwards from Santa Catarina state, through Rio Grande do Sul state and into Uruguay. Similarly to the Ribeira belt, the Dom Feliciano belt consists of supracrustal and basement rocks, accreted and metamorphosed during the Paleo to Neoproterozoic (Hartmann et al., 2000). Whilst the majority of the Brazilian part of the belt is found onshore adjacent to the Pelotas basin, the northern part of the belt borders the western region of the Santos basin. This part of the belt consists largely of syn-tectonic granitic batholiths, such as the Florianopolis batholith.

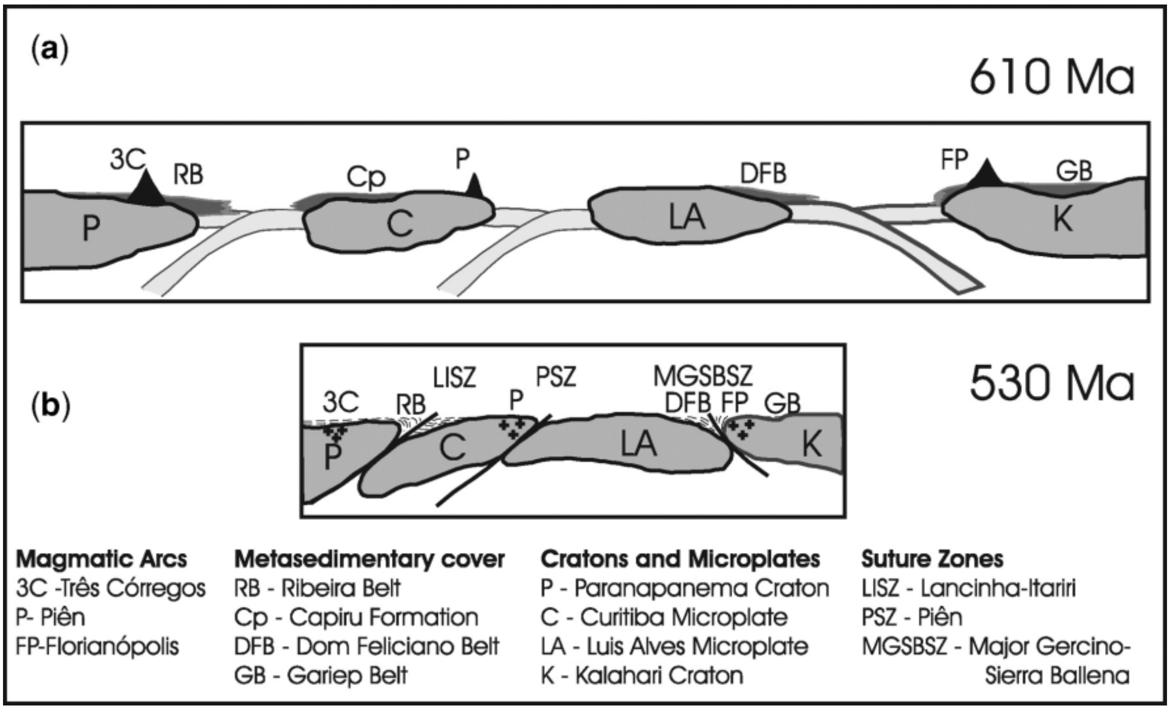


Figure 2.9 – simplified cross section illustrating pre-and post-collision positions of the major geologic units of south-eastern Brazil and south-western Africa (Basei et al., 2008).

2.3.1.4 The Florianopolis Batholith

The Florianopolis batholith, found in contact with the Dom Feliciano belt in the Santa Catarina state, south of the Luis Alves craton, was intruded at 610 – 580Ma, based on U-Pb dating of zircons. It is interpreted to be a syn- to post-orogenic (da Silva et al., 2005b) batholith and consists of crustally derived, calc-alkaline granites (da Silva et al., 2000). The batholith came into tectonic contact with the Dom Feliciano belt approximately at 600Ma along the Major Gercino Shear zone (Basei et al., 2008; Passarelli et al., 2011). The batholith is one of a series that formed in the Neoproterozoic from magma created as oceanic crust was subducted under the Kalahari craton. Whilst these batholiths are found in present day south America, they are thought to have originated on the eastern side of the Adamastor ocean (Basei et al., 2008). In the southeast part of Florianopolis state, Neoproterozoic to early Paleozoic volcano-sedimentary rocks of the Campo Alegre Formation are found overlying the granite (Basei et al., 2008; Raposo et al., 1998). The Campo Alegre formation is thought to relate to a late collisional magmatic episode (Kaul and Cordani, 2008), similar to those described for the Ribeira belt (Leite et al. 2007).

2.3.2 Major structures

The terranes of the Ribeira belt are separated by large scale shear zones, such as the Central Tectonic Boundary (Fig. 2.7). These shear zones formed as terranes accreted, and many appear to have been reactivated later in the Brasiliano orogeny (Heilbron et al., 2008). A summary of these can be found in Passarelli, et al (2011). These shear zones are typically top-to-the northwest thrust faults or dextral transpressional faults. Mylonites are extensive along these structures, due to the amphibolite to granulite facies conditions under which they formed. Mylonites could potentially be very important structures that may influence the development of brittle structures, as their mineralogy and structure may lead to them being 'easy to reactivate' (Holdsworth et al., 2001).

2.4 Evidence for Rifting Onshore

The onset and nature of Gondwana breakup in Brazil is the main focus of this study. Rifting is thought to have begun during the Early Cretaceous, between 135 and 130Ma, based on the ages of sediments in the South Atlantic offshore basins (Fig. 2.18). Breakup is thought to have been complete by lower Aptian times, approximately 125Ma (Modica and Brush, 2004). An understanding of the structures formed relating to Atlantic rifting is crucial in order to understand the development of the offshore basins and potential hydrocarbon prospectivity of the margin. In this section, syn-rift refers to the onset and development of the rift, which led to the breakup of Gondwana, and the initiation of what is now the Atlantic ocean. Post-rift refers to structural and stratigraphic events which have occurred following breakup.

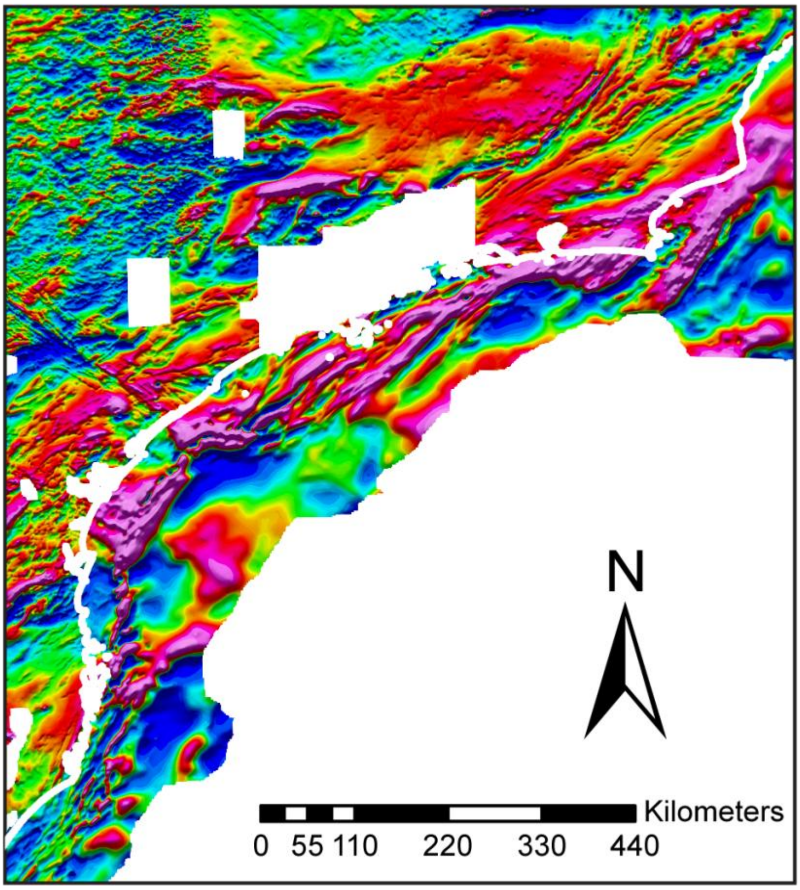


Figure 2.10 – Magnetic data for south-eastern Brazil (Bizzi et al., 2003). Note the strong NE-SW trend of magnetic anomalies which extends into the offshore. The NW-SE oriented magnetic anomalies to the west (in left of the map) represent the Ponta Grossa arch.

3 major dyke swarms that were intruded during the early rifting have been extensively studied. These dyke swarms comprise the main evidence for Mesozoic events onshore. In the Paraná basin, an intracontinental sedimentary basin initially formed during the Silurian, with depocentres active until the Cretaceous; lower Cretaceous flood basalt volcanism is associated with these dyke swarms as are the large basalt flows in the offshore basin.

Whilst rift to drift transition took place during the lower Cretaceous, tectonic events continued on the margin. Many authors (Riccomini et al., 1989; Zalán and Oliveira,

2005) refer to these events as individual rifting events. For clarity, and to separate them from Atlantic rifting, which is the main focus of this thesis, I refer to these tectonic events as being 'post rift'.

Post-rift structures comprise mainly the Late Cretaceous to Eocene-aged ‘continental rifts of south-eastern Brazil’ (Zalán and Oliveira, 2005). The faults that bound these rifts formed concurrently with large-scale uplift of the rift shoulders leading to the development of the modern day Serra do Mar. Igneous intrusions of Upper Cretaceous to Eocene age are also found onshore, forming dykes and alkaline plutons. Neotectonic faults, dating from the Neogene to the Quaternary are found across the margin, and were likely to have been caused by far-field stresses relating to the Andean orogeny (Cobbold et al., 2001; Riccomini et al., 1989). Many of these post-rift structures that have formed in the on- and offshore are thought to have been influenced by the reactivation of basement structures and Mesozoic rift-related faults (Cobbold et al., 2001).

2.4.1 Syn-Rift Structures

2.4.1.1 Dyke Swarms

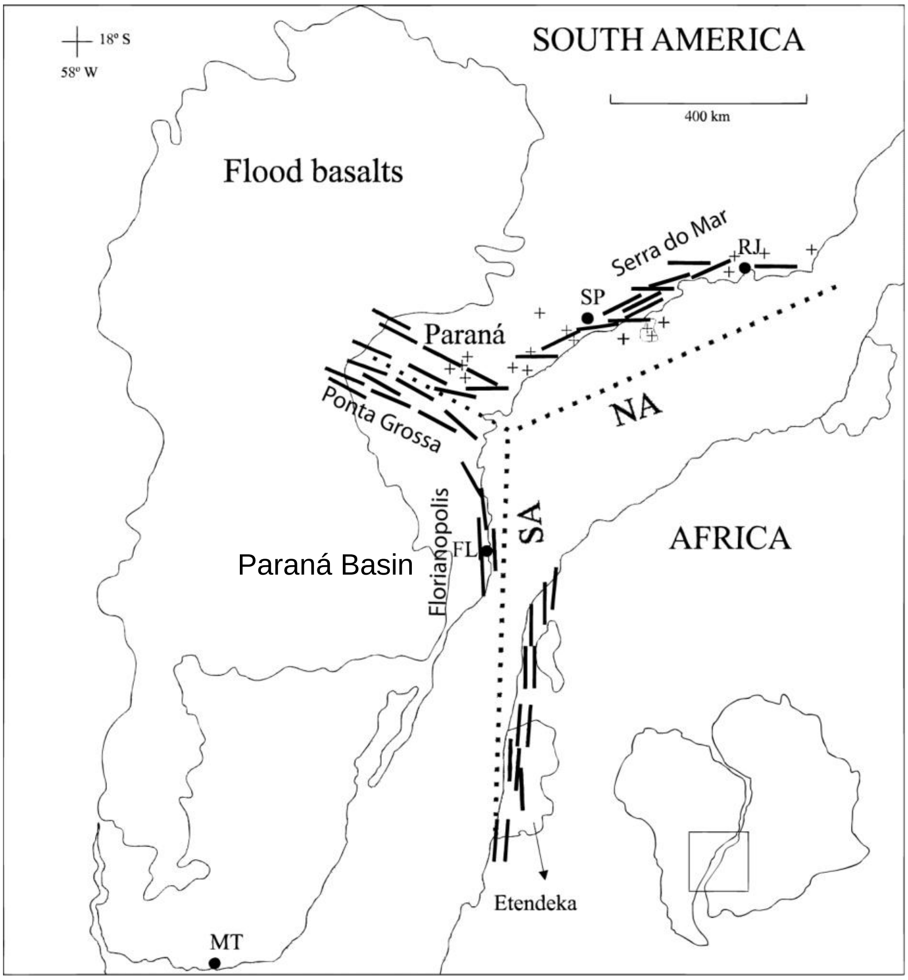


Figure 2.11 – Dyke swarms in south-eastern Brazil and south-western Africa, correlated to pre-drift geometries (Coutinho, 2008). NA = North arm (the Serra do Mar swarm, SA = south arm (the Florianopolis swarm), PGA = Ponta Grossa arch. Coutinho (2008) suggests these dyke swarms form a triple junction.

Large regional dyke swarms are frequently associated with continental rifting worldwide (White and McKenzie, 1989). On the south-eastern Brazilian margin, three major dyke swarms crop out onshore (Fig. 2.11), and it has been proposed that these are related to a 'triple junction' (Burke and Dewey, 1973; Coutinho, 2008). There is still some debate as to whether this triple junction formed as a result of a mantle plume, as in the 'Burke and Dewey' model, or was a result of continental rifting processes (Hawkesworth et al., 2000). The dykes are typically tholeiitic dolerites, formed between 135 and 125Ma (whole rock Ar-Ar and K-Ar) (with some exceptions). The dyke swarms are, from south to north: the NNE-SSW trending

Florianopolis dyke swarm; the NW-SE trending Ponta Grossa dyke swarm; and the NE-SW trending Serra do Mar dyke swarm (Fig. 2.10).

Whilst these dyke swarms are not the only intrusive igneous features in the region, they do form the earliest onshore evidence for Mesozoic continental rifting, as no older rift-related faults or dykes, other than those formed as part of intracontinental rifts such as the Paraná Basin have been documented. It is important to distinguish rift-related structures from non-rift related dykes through field and petrological observations, and from previously published data. In addition to the Mesozoic dykes, other magmatic events have been documented in the study area. Precambrian, syn-orogenic dykes have been recorded towards the south of the area, and in the Ribeira belt, post-rift alkaline magmatism has been observed (Coutinho, 2008). Some authors relate the origin of these dyke swarms, and the volcanism in the Paraná basin to the activity of the Tristan de Cunha plume, a mantle plume thought to be responsible for the development of the Walvis ridge, and the Rio Grande rise to the south of the area (Davison, 1999).

2.4.1.1.1 The Florianopolis dyke swarm

The Florianopolis swarm crops out mainly in the Santa Catarina state, mostly on Santa Catarina Island. Dykes generally trend NNE-SSW, parallel to the coastline, although a small number of NW-SE dykes are observed. Florianopolis dykes display a wide variation in width, from sub-metre thicknesses to over 100m. They are typically doleritic in composition and Ar-Ar dating of plagioclase suggests that they were intruded between 129 and 119Ma (Raposo et al., 1998) which is younger than the youngest magmatism in the Paraná basin (see section 2.4.1.3). Based on the study of magnetic fabrics within the dykes, flow within the majority of the dykes is thought to be vertical to sub-vertical, and the source of the magma is thought to lie beneath Santa Catarina Island (Raposo, 1997).

2.4.1.1.2 The Ponta Grossa swarm

The Ponta Grossa swarm is found mainly in the Paraná state, where it runs north-westwards from the coastal region under the Paraná basin (Fig. 2.10). Dykes in the swarm are thought to be responsible for feeding the early Cretaceous flood basalt magmatism in the basin. Most dykes in the swarm are aged approximately between 131 to 129 Ma, coeval with basalts in the Paraná basin, although dykes were intruded as recently as 120 Ma, based on Ar/Ar dating of plagioclase (Renne et al., 1996)

2.4.1.1.3 The Serra do Mar swarm

The Serra do Mar dyke swarm runs NE-SW through Rio de Janeiro and São Paulo states (Fig. 1.10) and the dykes trend approximately parallel to large scale basement structures. Some authors consider these basement weaknesses to favour dyke intrusion in this trend (Strugale et al., 2007). Dykes are typically tholeiitic dolerites, up to 30m wide (Coutinho, 2008), and intrusion ages are between 120 and 130Ma (Ar-Ar dating of samples analysed by laser ablation)(Turner et al., 1994). Younger post-rift alkaline magmatism, related to late Cretaceous-Tertiary rifting is also common in this area, forming dykes and plutons (Riccomini et al., 2005). Typically, these younger dykes are lamprophyres, and their mineralogy enables them to be distinguished from the older syn-rift dykes (Coutinho, 2008). Whilst most syn-rift dykes in the Serra do Mar swarm trend NE-SW, approximately N-S trending dykes can be seen around the Resende and Volta Redonda regions. These N-S trending dykes have been dated as old as c. 193Ma and as young as 130Ma (Guedes et al., 2005) suggesting that they either represent pre-rift magmatism or features formed during the very earliest stages of continental rifting

2.4.1.2 Syn-rift Faulting

Evidence for syn-rift faulting and fracturing in the Ribeira belt or the Florianopolis region has not been reported in the literature. Faults in the Ponta Grossa region are the most extensively studied brittle structures in the region (Strugale et al., 2007). The 'Ponta Grossa arch' is a NW-SE trending structural high which occurs in the Paraná basin. To the south, the Ponta Grossa arch cuts across the western end of the Ribeira belt, in the Paraná state. Although it is referred to in the literature as an 'arch', the Ponta Grossa arch consists of large, NW-SE trending dextral oblique faults, and the Ponta Grossa dyke swarm as described above.

Two phases of faulting in the Ponta Grossa region have been proposed by Strugale et al (2007), with a lower Cretaceous age for the first (D1) event, and an upper Cretaceous age for the second (D2) event. The D1 event is thought by Strugale et al. (2007) to relate to the continental rift, and the principal stress direction $\sigma 1$ is thought to have rotated clockwise during this period, from a NNW-SSE initial orientation to a roughly N-S orientation. Strike slip faults formed before this rotation have a NW-SE, or NE-SW trend, whereas faults formed after this rotation are more likely to be oriented N-S (Strugale et al., 2007). Based on cross-cutting relationships with stratigraphy in the Paraná Basin, Strugale et al also show that faults parallel to dykes in the Ponta Grossa region are contemporaneous with the dyking event

Faulting continued to occur across the margin during and after the magmatic events that affected the margin during the lower Cretaceous (Davison, 1999). See section 2.4.2 for further discussion of the post-rift tectonics.

2.4.1.3 The Paraná Basin

The Paraná basin is a large, N-S trending intercontinental sedimentary basin in south-eastern Brazil, Paraguay and Uruguay (Fig. 2.5). It correlates with the Etendeka basin in Namibia (Peate, 1997) (Fig. 2.10). The two basins were originally formed in Gondwana and split by Atlantic rifting. The Paraná basin formed in the late Ordovician, and continued to be an active depocentre for sediments until the Upper Cretaceous (Milani and De Wit, 2008). In Brazil, sediments in the Paraná basin comprise 6 sedimentary megasequences, separated by major erosional unconformities. The oldest sequences represent marine transgressions and regressions, formed during the Silurian and Devonian. During the Carboniferous to Permian, the sediments show evidence of large scale glaciations. During the late Permian, coal and black shales were formed in the basin, suggesting deltaic or lacustrine conditions (Milani and De Wit, 2008). In the Mesozoic, the region became more arid, leading to the deposition of continental sandstones during the Cretaceous (Milani and De Wit, 2008; Scherer, 2000). During the Upper Cretaceous, the large scale, rapid outpouring of flood basalts formed the Serra Geral formation, which has been dated at approximately 135Ma (Thiede and Vasconcelos, 2010).

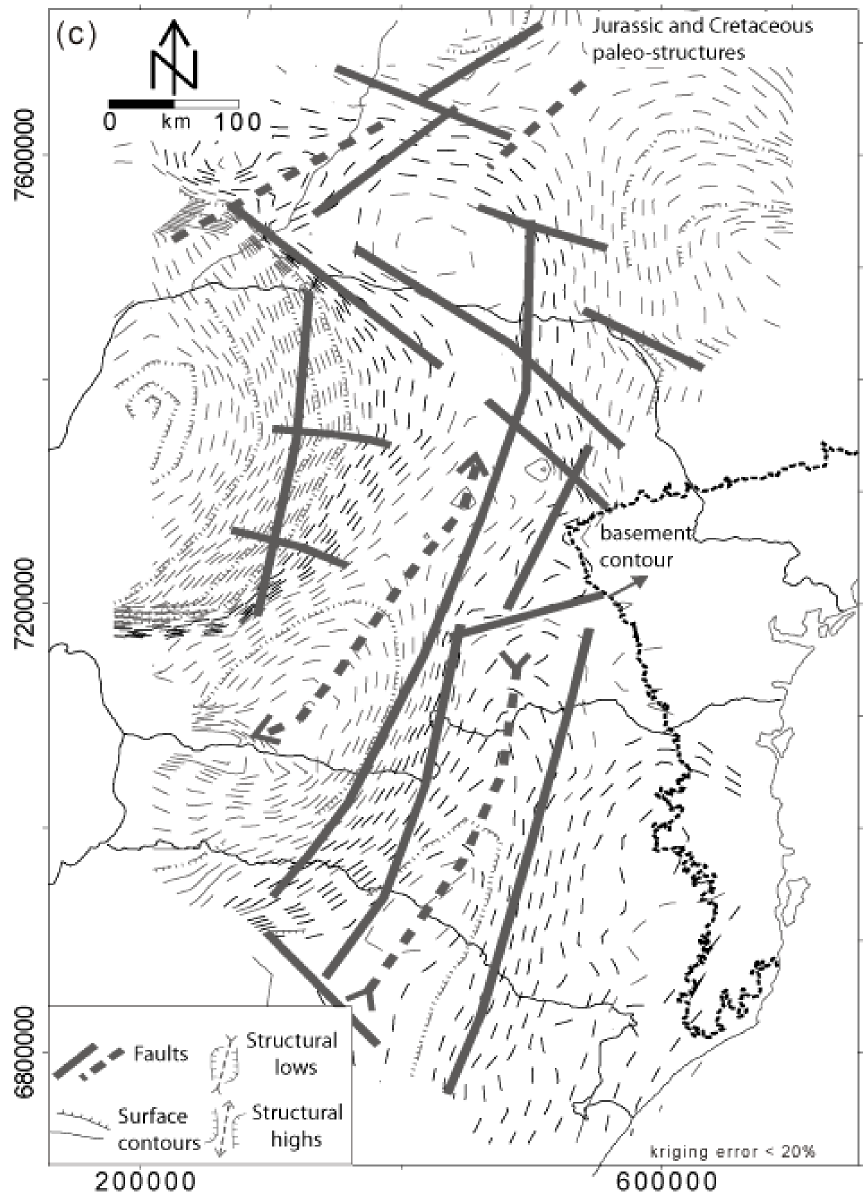


Figure 2.12 – Jurassic and Cretaceous structures of the Paraná basin (Artur and Soares, 2008). NNE-SSW faults and lineaments are most prominent towards the south of the basin, whilst the NW-SE faults of the Ponta Grossa arch are a strong influence further north. The edge of the basin is marked by the thick black dashed line labelled 'basement contour'.

The present day extent of the Parana basin is largely underlain by the São Francisco craton. The basin is thought to have evolved due to a combination of plate margin processes and intraplate subsidence (Rostirolla et al., 2003). The dominant structural feature of the basin in the Paraná state is the NW-SE trending Ponta Grossa arch as described above (Strugale et al., 2007). Towards the east of the basin in the Paraná state, NE-SW-trending faults cut the basin which have a similar orientation to basement structures in the Ribeira belt (Rostirolla et al., 2003).

Due to the large amount of sediment cover, little is known about the faults that controlled the early evolution of the basin. Despite this, both NE-SW trending structures of Devonian age, which have been reactivated during the Mesozoic and Cenozoic, and N-S trending Cretaceous structures have been inferred on the basis of sedimentary thickness variations and on the geometric architecture of the basin (Artur and Soares, 2008).

2.4.2 Post-rift tectonics

Throughout the Late Cretaceous and Cenozoic, multiple stress orientations have been inferred in southeastern Brazil; based on palaeostress analysis, and the orientations of structures of known ages (Ferrari, 2001; Riccomini and Assumpção, 1999; Riccomini et al., 1989). 4 main tectonic events are thought to have occurred on the margin following breakup (Ferrari, 2001). These events have different kinematics, recording changes in the regional stress-field. The earliest event is thought to be a Late Cretaceous to Eocene sinistral transtensional event (Figure 2.14), which formed NE-SW trending rifted basins onshore. This event was followed by two phases of NE-SW extension. The first event was believed to be extensional during the Eocene and Oligocene, whilst the second showed dextral-oblique kinematics during the Pleistocene (Ferrari, 2001). The most recent events are classified as Neotectonic, and display more regional variation, ranging from E-W extension during the Holocene, to dextral transpression seen at the present day (Ferrari, 2001; Riccomini et al., 1989; Saadi et al., 2002). These events will be discussed in more detail below.

Evidence for post-rift faulting is more commonly seen onshore than for syn-rift faulting. The dominant post-rift event (the first of the four events mentioned above) formed the continental rift system of south-eastern Brazil (Zalán and Oliveira, 2005) and occurred in the Late Cretaceous and early Cenozoic; a significant period of time after the main Atlantic rifting phase. The age of this deformation is thought to be between lower Cretaceous and Eocene, and is determined from biostratigraphy on sediments in the onshore basins (Filho et al., 2010), dating of exhumation events by apatite fission track analysis (Gallagher and Brown, 1999), and study of fish faunas (Ribeiro, 2006). The basins are thought to have been strongly influenced by the reactivation of basement structures. Post-rift uplift and extensional faulting, which may or may not result in the formation of onshore rift basins is common on other continental margins, such as the east Greenland, and Norwegian continental margins (Japsen and Chalmers, 2000; Osmundsen and Redfield, 2011). Contemporaneously with the formation of the onshore sedimentary basins, large scale regional uplift formed the Serra do Mar, and alkaline magmatism led to the formation of dykes, sills and plutons. Tectonism continued throughout the Cenozoic, and active faults are still present today (Saadi et al., 2002).

2.4.2.1 The continental rift system of south-eastern Brazil

The continental rift system of SE Brazil consists of a series of elongate, NE-SW trending rift basins, aligned parallel to Ribeira belt structures. The largest basin, at 170km long is the Taubate basin (Fig. 2.13). The basin preserves a record of continental sedimentation, deposited from the Eocene to the present, with early sediment consisting of lacustrine muds and more sandy sediments having formed later (Filho et al., 2010; Padilha et al., 1991). The faults at the margins of the Taubate basin switch from being SE-dipping to NW-dipping faults along its length. In both cases, the faults and hangingwall sediments display half-graben geometry (Padilha et al., 1991).

The other basins of the continental rift system of southern Brazil, whilst smaller than the Taubate basin, show similar structural features and are of a similar age. The reactivation of basement structures is also thought by some authors to have been influential in the development of these basins (Hiruma et al., 2010). These basins include, from west to east: the Curitiba basin; the Resende basin; the Volta Redonda basin; and the Guanabara graben. Many other basins have also been mapped. These basins are also sites of Neotectonic activity (Riccomini et al., 1989) indicating that further reactivation has occurred.

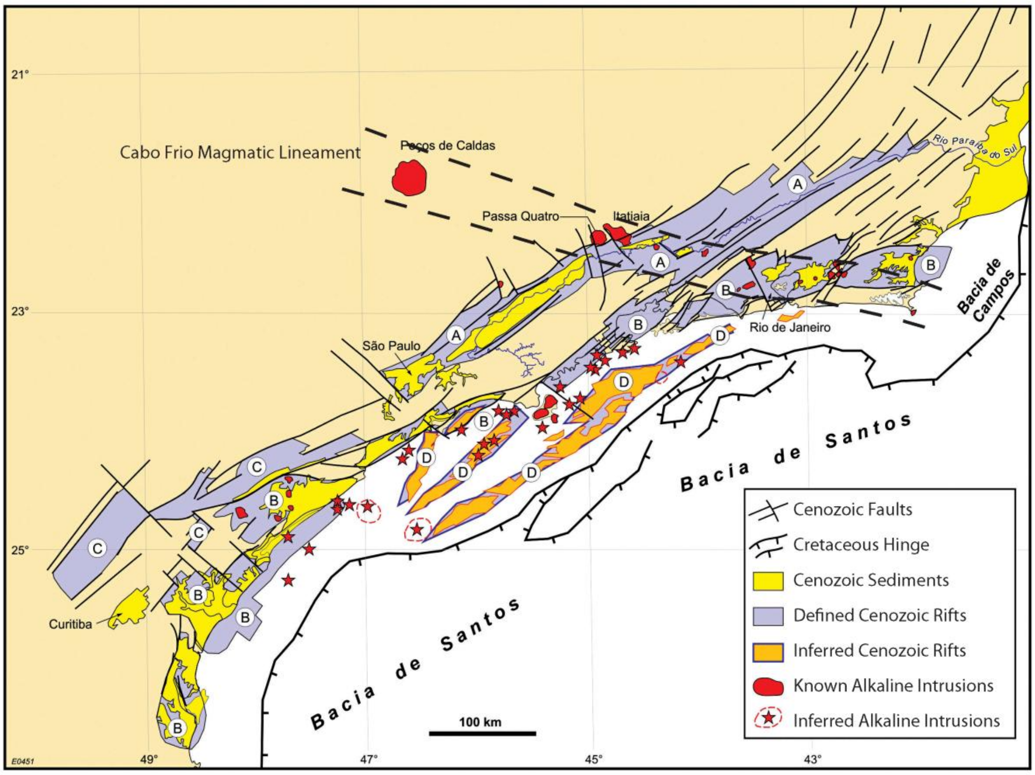
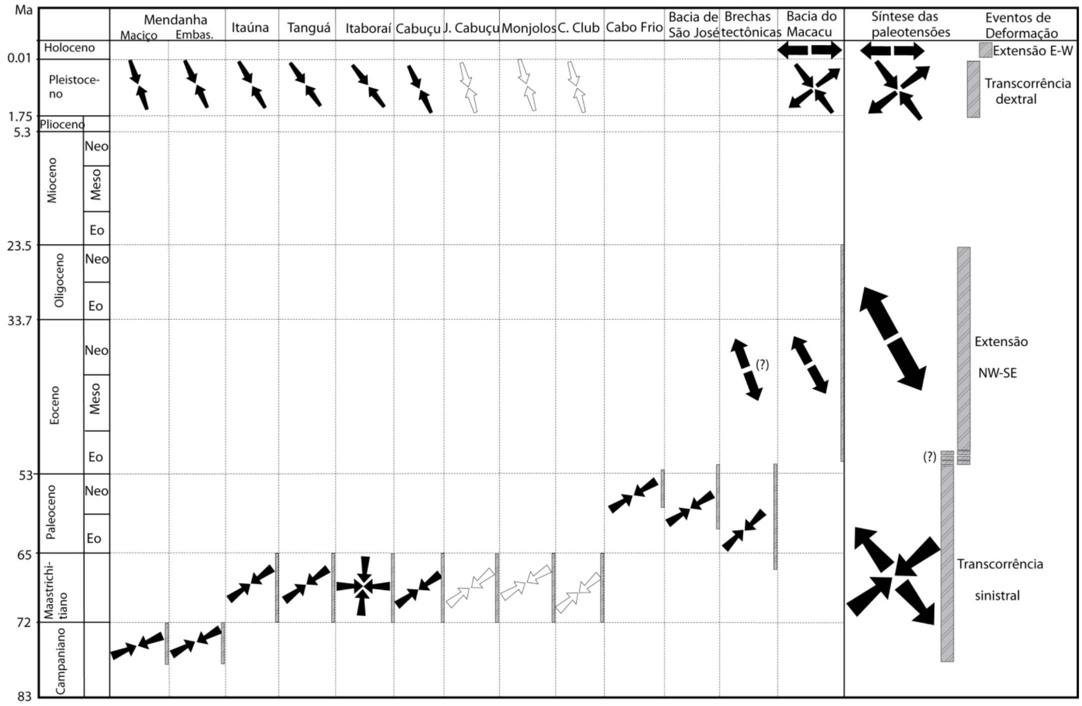


Figure 2.13 – The continental rift system of south-eastern Brazil (Zalán and Oliveira, 2005). Faults and basins trend closely parallel to the structure of the Ribeira belt, whilst large alkaline intrusions form a magmatic lineament thought to relate to the movement of the Tristan de Cunha plume head.

2.4.2.2 Post-Rift Faulting

The style of faulting associated with the post-rift (i.e. post breakup) events is complex, and changes from sinistral transtension in the late-Cretaceous-Eocene event, to normal faulting throughout most of the Eocene (Ferrari, 2001). More recent faults have more complex kinematics, with some thought to be sinistral oblique and others dextral (Ferrari, 2001; Saadi et al., 2002).

Some Cenozoic faults onshore have been shown to reactivate pre-existing basement structures, such as mylonites (Gontijo-Pascutti et al., 2010). This suggests that pre-existing basement structures do at least locally play a role in the development of later structures. Other faults have been studied using apatite fission track analysis, and multiple uplift events have been recorded, suggesting brittle reactivation (Hiruma et al., 2010)



2.4.2.3

Figure 2.14 – Changing paleostress orientations during the development of the Guanabara graben, Rio de Janeiro (Ferrari, 2001). The post-rift initiation and development of onshore basins in SE Brazil is typically associated with multiple changes in the stress field, although the origins of these changes are not well understood. The Guanabara graben is found to the north of Rio de Janeiro, in the Serra do Mar region.Regional Uplift

The Serra do Mar forms a large, coast-parallel mountain belt, with peaks over 2000m high. Fission track studies (AFTA), together with studies of icthyofaunas, have shown that this uplift occurred approximately 30Ma after rifting, during the late Cretaceous and early Cenozoic (Hackspacher et al., 2004; Ribeiro, 2006). The causes of this uplift and that of other uplifted passive margins around the world are not well understood

The uplift of the Serra do Mar region played a significant role in the stratigraphic development of the margin because it supplied continental-derived sediment into the post-rift Santos basin offshore (Karner and Driscoll, 1999). Several different uplift events are thought to have occurred, reactivating brittle faults and possibly Ribeira belt structures (Hiruma et al., 2010; Tello Saenz et al., 2003). This reactivation also played a significant role in the development of the onshore sedimentary basins, and the post-rift structural and stratigraphic development of the Santos basin (Mohriak et al., 2008).

Large scale landforms such as fault scarps and ‘peneplanation surfaces’ in the Serra do Mar have been interpreted with the aim of trying to pick faults relating to the uplift process (Zalán and Oliveira, 2005). See Fig. 2.13 for a map of faults picked using this method.

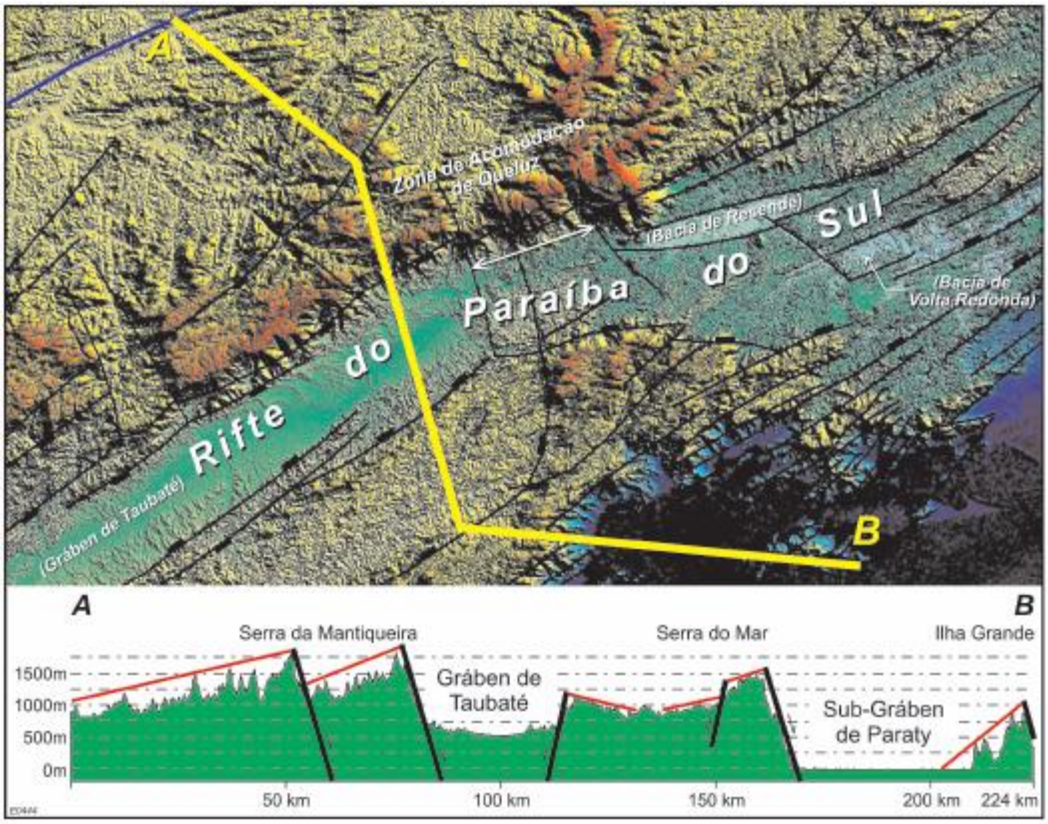


Figure 2.15 – Topographic cross section of the Taubate graben, the Serra do Mar and the Serra da Mantiqueira (Zalán and Oliveira, 2005). Faults are picked from topographic lineaments and also from vertically exaggerated topography. Whilst faults that have been picked using this method do exist, e.g. the Taubate Graben, it is my view that the extent to which this data is vertically exaggerated presents an unrealistic view of the topography of the region, and that this does not constitute a reliable method for picking faults in such highly weathered topography (see Chapter 4 for more discussion on this topic).

2.4.2.4 Post-rift Magmatism

The Serra do Mar region was intruded by alkaline magmas during the post-rift period from 85 to 60Ma (Riccomini et al., 2005). These magmas were intruded as dykes, and as larger bodies, such as the Pocos de Caldas, and Morro de São João plutons. These intrusions form the ‘Cabo Frio magmatic lineament’, which is thought to correlate with the Trinidade hot-spot track (Filho et al., 2005). These larger intrusions are mostly syenitic in composition (Riccomini et al., 2005).

Dykes formed in the Serra do Mar region during the post-rift period are typically narrow, NE-SW-trending, lamprophyre composition dykes that are rich in amphibole and phlogopite-biotite. They are commonly found in regions near the larger alkaline intrusions (Coutinho, 2008).

2.4.2.5 Neotectonics

Neotectonic faults show that deformation is continuing to the present day in the Ribeira belt. The majority of these faults form in response to an E-W oriented principal stress direction (Riccomini and Assumpção, 1999), and NE-SW oriented transpressional faults are common, reactivating earlier brittle structures (Salamuni et al., 2003). Rotations of this stress field during the Holocene have been suggested (Salvador and Riccomini, 1995), and some maps of currently active faults show regional variations in kinematics for faults of the same trend (Saadi et al., 2002) Neotectonic faults are typically identified by their cross-cutting of recent stratigraphy in sedimentary basins (Riccomini et al., 1989).

2.5 Offshore rifting

The Santos basin sits on a large continental rifted margin (Fig. 2.5). Its early evolution was characterised by large amounts of extension, the outpouring of lava flows, and the formation of a large, shallow sea which formed a salt basin during the Aptian (Mohriak et al., 2008). The basin is over 600km wide (Davison, 1997) and the sediments (dating from the lower Cretaceous to Recent sea floor sediments) are up to 5.3km thick (Contreras et al., 2010).

The basin extends from the Cabo Frio peninsula to the north, where it borders the Campos basin, to the Florianopolis lineament to the south – a large linear high, separates the Santos basin from the Pelotas basin (Davison, 2007) (Fig. 2.5) .

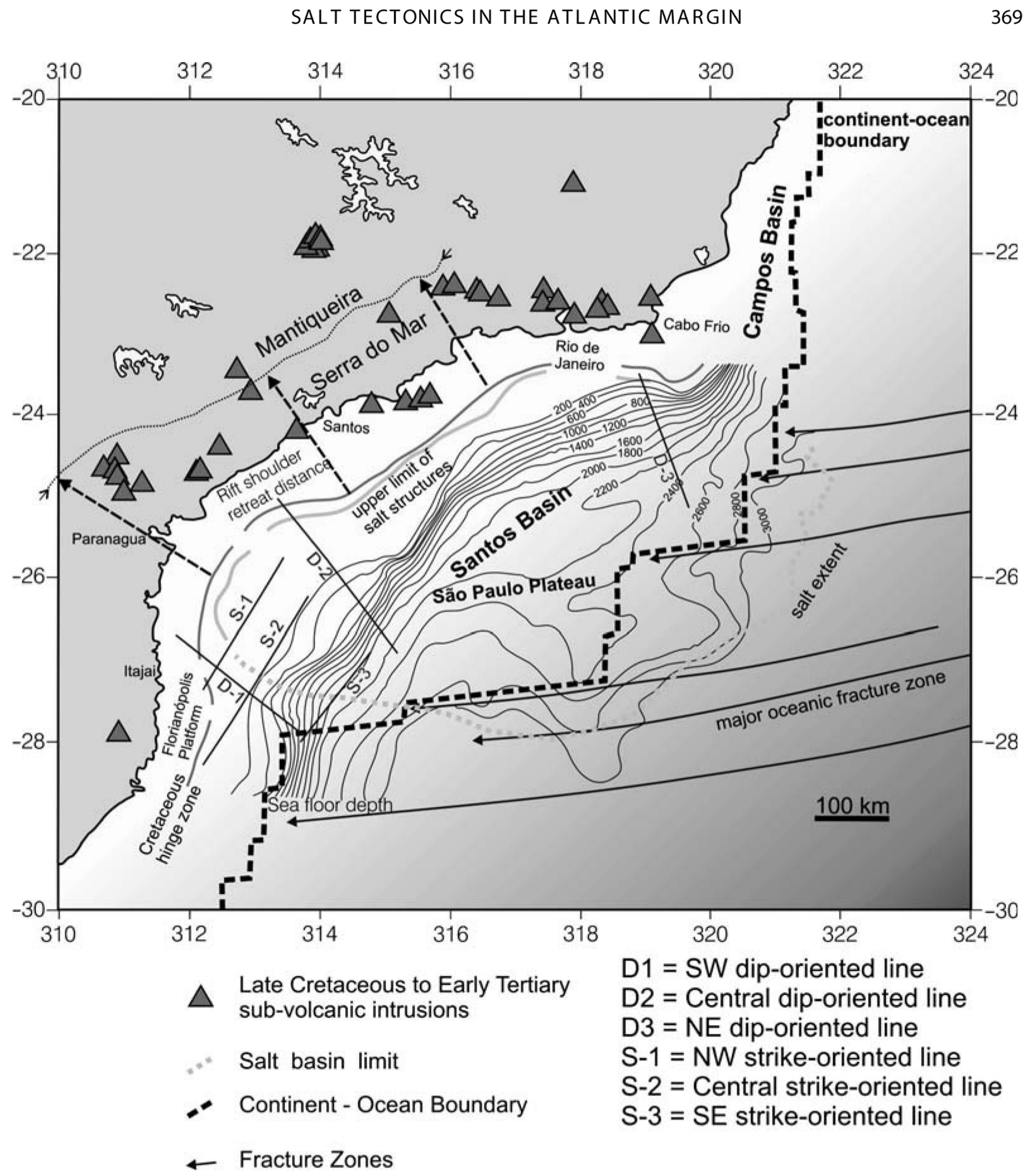


Figure 2.16 – Bathymetry and key features of the Santos Basin (Mohriak et al., 2008).

When compared to other basins on the margin, the Santos basin is significantly wider (600km). Its conjugate margin, the Namibe basin in Angola is also much narrower (less than 100km (Davison, 2007) and the two basins form a wide-narrow margin pair. By contrast, the Campos and Pelotas basins are relatively narrow, and of a similar width to their conjugate basins on the African margin (Davison, 1997). The Santos – Kwanza margins are thought to have developed due to large amounts of crustal stretching during the early rift, and form a wide-narrow margin pair. The cause of this large amount of stretching (when compared to other South Atlantic margins) has been attributed to a number of possible causes, including the presence of pre-existing lithospheric and crustal weaknesses, differential heat flow during early rifting, and the kinematics of continental rifting (Davison, 1997).

The south Atlantic margins are thought to have developed in 5 main stages – Pre-Rift (pre-Barremian), Syn-Rift (Barremian to Lower Aptian), Sag (Mid-Upper Aptian), Post-Rift (Upper Aptian-Albian), and Drift (Albian-Cenomanian) (Contreras et al., 2010; Modica and Brush, 2004; Mohriak et al., 2008). These stages represent different structural and stratigraphic processes during the evolution of the continental rift, the development of the early south Atlantic ocean, and the longer term evolution of the passive continental margin (Contreras et al., 2010)

2.5.1 Santos basin stratigraphy

The stratigraphy of the Santos basin is fundamental to its hydrocarbon prospectivity. Whilst oil and gas are found in syn-rift tilted fault block structures, the overlying salt, carbonate reservoir rocks and lacustrine source rocks are all key components in the development of the sub-salt plays (Scotchman et al., 2010). Fig. 2.18 shows the stratigraphy of the Santos basin.

Sediments in the Santos basin reach thicknesses of up to 5300m. The onset of rifting in the Santos basin was marked by the outpouring of large amounts of lava, both in the Paraná basin, and into the Santos basin itself. In the Santos basin, these lavas are known as the Camboriu formation, and are interlayered with volcaniclastics, continental siliclastic, and lacustrine sediments (Chang et al., 1992; Mohriak et al., 2008). These lavas are thought to be Neocomian in age (approx 130Ma), and may correlate with the intrusion of dykes in the basement onshore, and the flood basalt volcanism in the Paraná basin (Guedes et al., 2005), although some view the Paraná volcanics as a pre-rift event (Mohriak et al., 2002). Igneous rocks in the Santos and other Brazilian basins are thought to have had a significant effect on hydrocarbon systems, due to their effect on heat flow, stratigraphy and fluid migration (Filho et al., 2008). Seaward dipping reflectors have been observed in the southern part of the Santos basin, highlighting the volcanic aspect of the margin (Jackson et al., 2000).

2.5.1.1 Syn-Rift Sedimentation

Following the eruption of the Camboriu formation, a ‘syn-rift megasequence’ was deposited during the Barremian and Aptian (130-112Ma). This megasequence consists of sedimentary rocks deposited during the gradual deepening of the Santos basin, and consists of continental lacustrine and shallow marine carbonate sediments (Contreras et al., 2010). The earliest syn-rift sediments are thought to be continental clastic sediments (Fig. 2.18), filling rift valleys created as the continent was extended during the Barremian to early Aptian. Alluvial fans and lacustrine sediments were formed. As extension continued, deltaic sandstones were deposited, followed by shelly limestones and shales, recording marine transgression during the early Aptian (Davison, 1999; Modica and Brush, 2004). Neocomian lacustrine rocks formed as the continental rift developed and are likely to be one of the major source rocks for oil in the Santos basin (Davison, 1999).

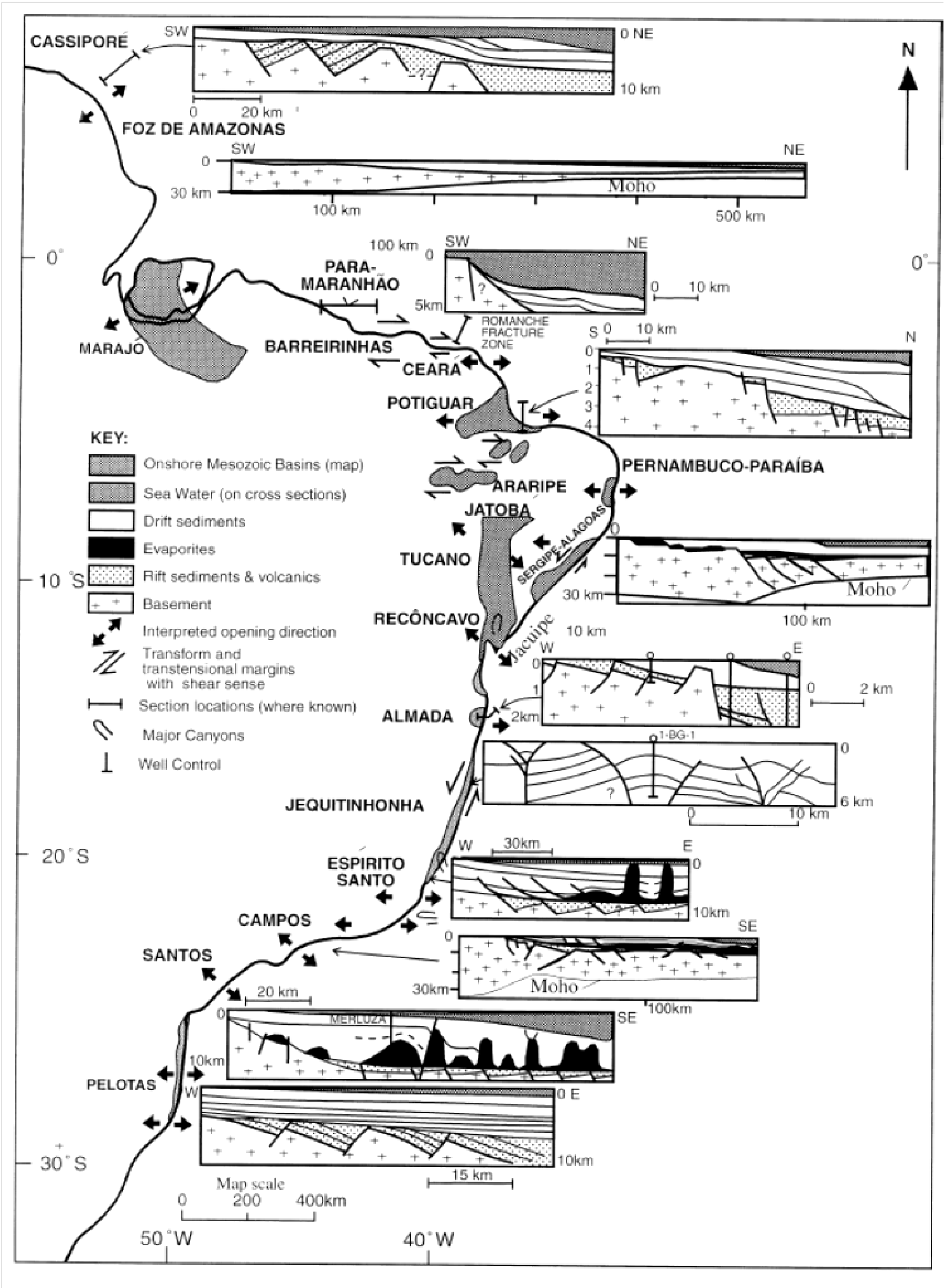


Fig 2.17 – Generalized cross sections through the basins on the Brazilian continental margin (Davison, 1997). Note the differences in scale between the sections, highlighting the differences in basin width. The Pelotas basin is considered to be a volcanic margin, with well-defined seaward dipping reflectors. The Santos, Campos and Espirito Santo basins contain large amounts of Aptian salt lying above syn-rift strata.

2.5.1.2 Sag

Following the deposition of the carbonate platform sediments, the entire basin is thought to have subsided thermally, leading to the deposition of relatively uniform thickness of sediments across the basin. These sag horizons consist of unfaulted reflectors dating to the early Aptian (Karner and Gamboa, 2007). They are made up of lacustrine and possible stromatolitic carbonates, and sit above an erosional unconformity on tilted fault-blocks and syn-rift graben fills (Contreras et al., 2010).

Large amounts of evaporites were deposited in the Santos basin during the late Aptian (Davison, 2007). These were formed in a shallow sea, thought to be isolated from basins to the north and south, possibly by the Cabo Frio and Florianopolis highs. Some salt in the basin is internally stratified, whereas some appears more massive, suggesting changes in marine conditions across the area (Modica and Brush, 2004). Evaporites are thought to have been deposited on a peneplain and are estimated to have originally been ~2000m thick prior to salt migration (Davison, 1999). Evaporites in the basin are fundamental importance to the pre-salt hydrocarbon system, as they provide the seal for many potential reservoirs (Gomes et al., 2009).

The mobility of this salt has had a significant effect on the structural development of the post-rift basin, with diapirs and withdrawal structures affecting the later stratigraphic development (Davison, 2007). Salt thickens towards the centre of the basin, and is thinner over the São Paulo plateau. Due to salt mobility, complete salt withdrawal is observed in a region known as the 'Albian Gap', which is thought to have originally been one of the areas where evaporite accumulations were thickest (Modica and Brush, 2004).

The thick salt deposition in the Santos basin impairs the quality of much of the seismic reflection data that have been acquired. Imaging below the salt is significantly affected by changes in salt thickness and stratigraphy, which in turn can limit the ability to interpret sub-salt reflection data. This will be discussed further in Chapter 6.

2.5.1.3 Post-Rift

Breakup in the Santos basin was complete by the Albian, as seafloor spreading propagated northwards. After cessation of salt deposition, sedimentation was strongly influenced by the uplift of the Serra do Mar, and the evolution of drainage systems onshore (Modica and Brush, 2004).

The earliest post-rift sedimentary rocks are called the Guarujá and Itanhaem formations (Modica and Brush, 2004). These were deposited in the Aptian and comprise carbonate platform sediments and continental clastics reflecting relatively low clastic inputs. Since the Late Cretaceous and Early Cenozoic, sedimentation has been increasingly dominated by continental clastic sediments in the near shore regions, and more fine grained sediments in the deepwater environment, possibly as a result of uplift and denudation of the Serra do Mar mountains (Modica and Brush, 2004).

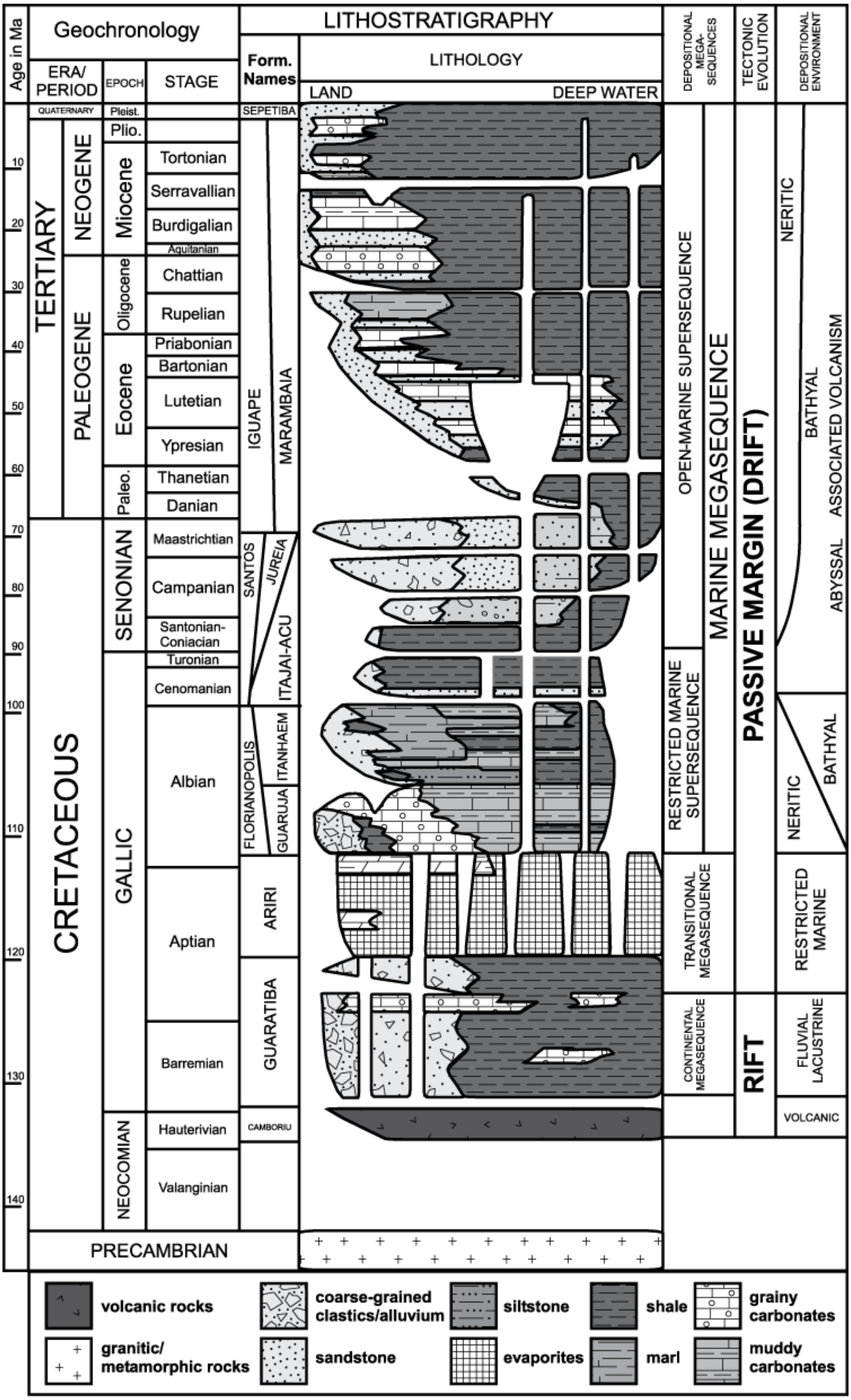


Figure 2.18 – Stratigraphic framework of the Santos and Campos basin (Modica and Brush, 2004).

2.5.2 Santos basin structure

2.5.2.1 Syn-Rift structures

Structures relating to the Atlantic rifting stage (Neocomian) of the Santos basin are found beneath the salt and sag horizons. The trends of syn-rift structures can be seen using gravity and magnetic data (Fig. 2.19), and basement structure is thought to be responsible for these trends (Karner and Gamboa, 2007). They form 3 main structural trends – NE-SW, NNE-SSW, and NW-SE. The NNE-SSW faults are synthetic and antithetic faults, which form many of the structural highs on which fields such as Tupi, Jupiter, and Carioca are found (Chang et al., 1992; Scotchman et al., 2010). Since the NE-SW and NNE-SSW faults lie at an oblique angle to the E-W extension direction, they may be transtensional in nature. In the nearshore region of the basin, some of the NE-SW faults have been identified as ceasing to be active by the middle-upper Barremian, before the deposition of evaporites in the basin (Contreras et al., 2010).

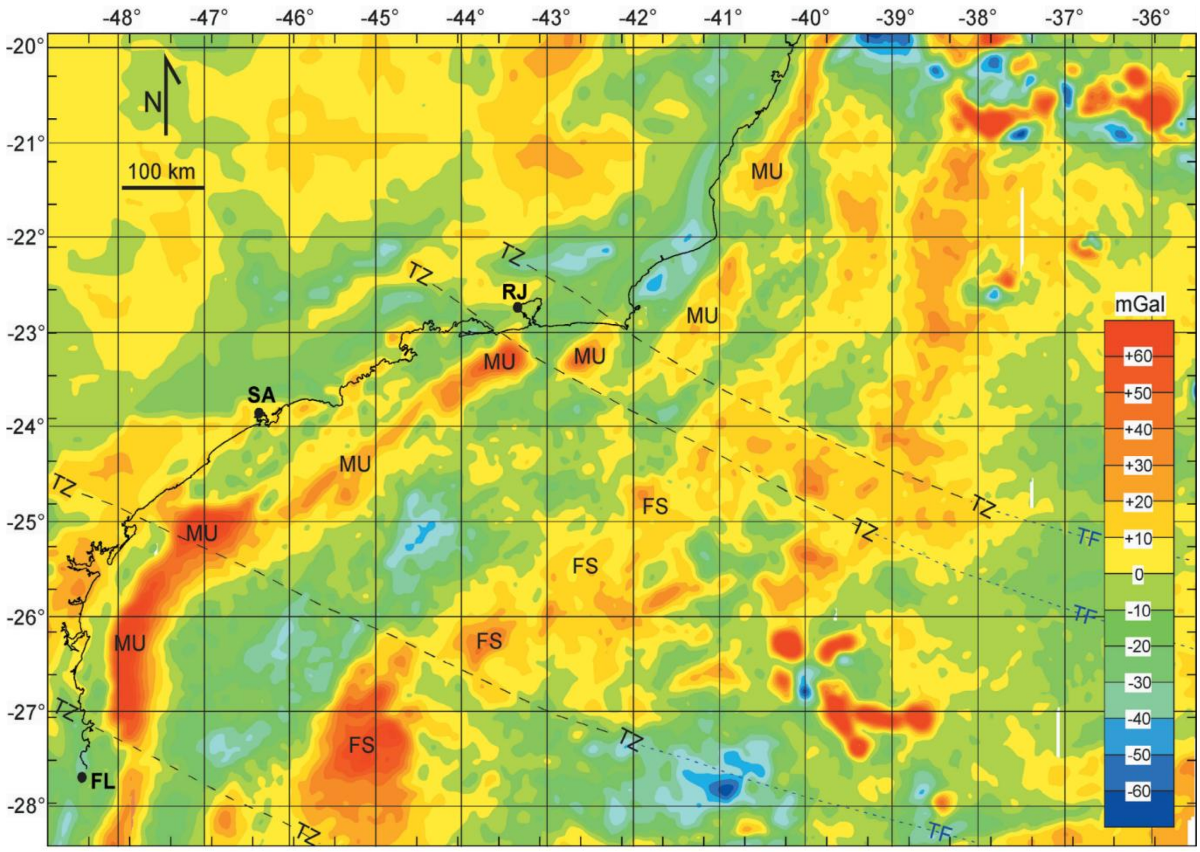


Figure 2.19 – 5th order residual of Bouguer gravity anomalies in the Santos and Campos basins (Meisling et al., 2001). NE-SW structural trends can be observed clearly onshore, near shore and further into the basin. TZ = NW-SE trending

transfer zones. MU = Moho uplift. FS = failed spreading ridge (as interpreted by Meisling et al (2001)).

In contrast to the synthetic and antithetic faults, NW-SE structural trends, again observed from gravity and magnetic data, are interpreted to be transfer zones, accommodating some of the oblique extension (Meisling et al., 2001). Some of these transfer zones are thought to crop out onshore, forming NW-SE oriented faults in the Ribeira belt located to the north of the basin (de Souza, 2008).

2.5.2.2 The São Paulo Plateau

The São Paulo plateau is a large (12,000 km^2) high in the centre of the Santos basin (Fig. 2.16). It consists of a series of uplifted tilted fault blocks, and was formed during the Barremian. Its evolution has been related to the initiation of seafloor spreading in the basin (Gomes et al., 2009; Scotchman et al., 2010). Some authors have suggested that ridges on the plateau may be formed from peridotite. Peridotite ridges on the Iberian continental margin have been suggested as evidence for low-angle normal faults accommodating large amounts of extension (Dean et al., 2000). See chapter 3.3.1.2 for further discussion on hyperextension

During the early rift, the São Paulo plateau formed a geographic high located between the Brazilian and African margins. As the rift evolved, Atlantic spreading became established to the east of the plateau, leaving it isolated on the Brazilian margin (Gomes et al., 2002). During early evolution of the plateau, the area experienced little clastic input and hence the development of a carbonate platform, which is a key reservoir for sub-salt oil and gas was favoured (Gomes et al., 2009). Structures on the São Paulo plateau, such as the Tupi and Sugar Loaf structures trend NE-SW, sub-parallel to regional basement trends (Busquet, 2011; Gomes et al., 2009). Transfer zones are thought to cross-cut these structures (Gomes et al., 2009).

2.5.2.3 Failed Ocean Spreading

Ocean spreading is thought to have initiated in the Santos basin during the Aptian (Mohriak et al., 2008; Scotchman et al., 2010) (Fig. 2.19). In these models, spreading was terminated when the main axis of switched outboard to the mid-Atlantic ridge. The axis of this spreading is thought to be NNW-SSE, and the spreading centre is thought to have been the result of high degrees of lithospheric thinning in the basin. Structures similar to this area of thinned lithosphere, also thought to relate to ocean spreading are thought to be found in other basins, notably the Faroe-Shetland basin (Scotchman et al., 2010), and the Red Sea, which is considered to be a modern day analogue for the early rifting in the Santos basin (Mohriak, 2011)

2.5.2.4 Peridotite Ridges?

Ridges of mantle rocks such as peridotite are thought to be a feature at many hyper-extended continental margins (Dean et al., 2000), and are thought to be present in the Santos basin (Gomes et al., 2009; Zalán et al., 2011a), though authors differ on their exact size and position Gomes et al suggest that a portion of the São Paulo plateau is composed of peridotite, whereas Zalan et al. proposed a margin parallel, elongate peridotide ridge in the distal regions of the Santos and Campos basins. The presence of exhumed peridotite may be considered to be evidence for low-angle detachment faulting during the rifting of the Santos basin. However, no dredged or drilled samples of peridotite have been reported from the Santos basin. Hyperextension of the Santos basin has been suggested by a number of authors (Reston, 2010; Zalán et al., 2011b), with stretching factors thought to exceed 4-5, based on estimates of crustal thinning (Reston, 2010). The causes and effects of hyperextended margins are discussed in chapter 3.3.1.2.

2.5.2.5 Sag

During regional thermal sag, the basin underwent widespread subsidence following the lithospheric thinning. This type of subsidence is common in rifted basins worldwide, and has been associated with stretching leading to thermal subsidence of the thinned lithosphere (White and McKenzie, 1989). Faulting associated with this subsidence has not been observed in the Santos basin (Karner and Gamboa, 2007).

2.5.2.6 Salt Tectonics

The mobility of salt after its deposition is a key feature in many basins worldwide. In the Santos basin, large salt diapirs have significantly affected later stratigraphy both during and after deposition. Early post-rift (Albian) sediments onlap onto salt structures, whilst younger sediments have been deformed by folding and faulting as a result of salt mobility. In addition, salt can act as a weak layer, decoupling deformation above and below it (Contreras et al., 2010; Davison, 2007).

2.5.2.7 Volcanic or non-volcanic?

Two end members have been recognised in terms of the volume of magma involved in rifting in continental margins (White and McKenzie, 1989): - magma-rich margins, such as the eastern US margin, and magma-poor margins, such as the Iberia-Newfoundland margin. These are termed ‘volcanic’ and ‘non-volcanic margins’ respectively. The Santos basin is often considered a magma-poor or non-volcanic margin. When compared to the Pelotas basin, there is a far smaller volume of volcanic rocks in the Santos basin. However, examples of seaward dipping reflectors have been published, and the presence onshore of regional-scale dyke swarms and the Paraná flood basalt basin suggest that igneous activity was important during the evolution of the margin. Whether or not the margin is regarded as volcanic can have strong implications for how rifting dynamics are interpreted, especially for the use of models developed to explain the development magma-poor margins such as Iberia-Newfoundland (Lavier and Manatschal, 2006). These implications relate to the high heatflows and igneous intrusion, which would normally be associated with volcanic margin formation, and which can affect lithospheric thinning, extension, and the development of faults during rifting (see chapter 3).

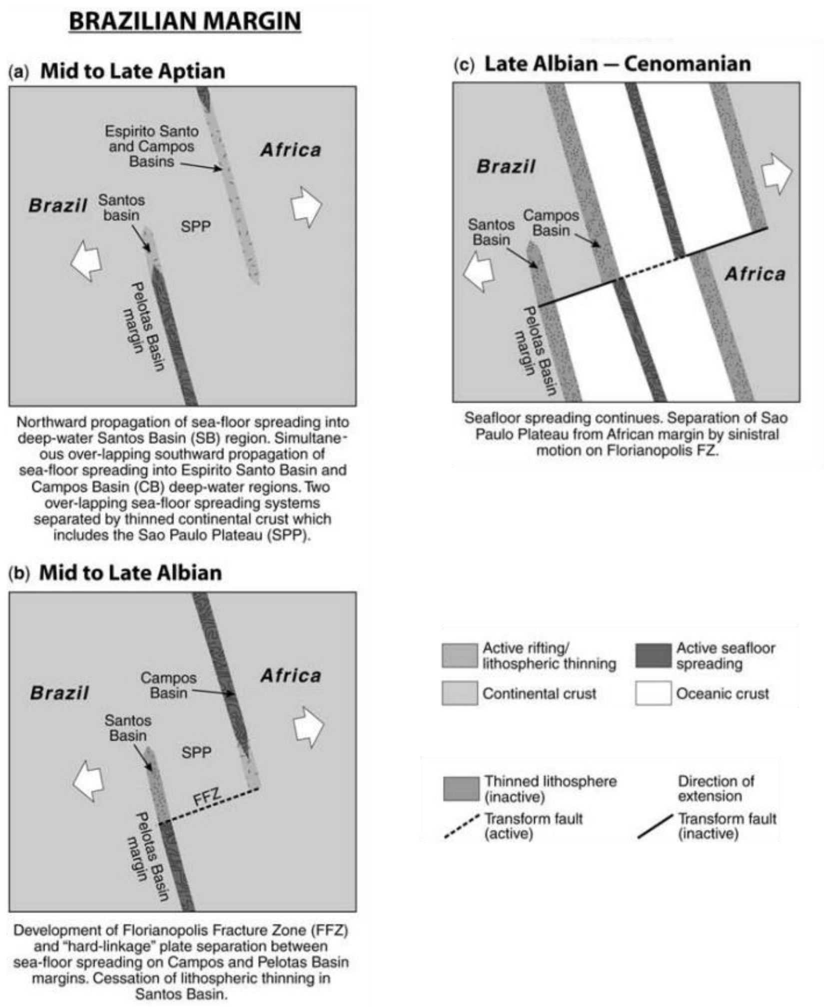


Figure 2.20. Ocean spreading in the South Atlantic, modified from Scotchman et al, 2010. Spreading initially propagates northwards into the Santos basin, before jumping to its current position in the central Atlantic.

2.5.3 Post-rift Tectonics

Post-rift structures in the basin are dominated by salt tectonics, although regional tectonics have also probably played a role. The development of transfer zones continued during the upper Cretaceous, as did the development of the 'continental hinge' – a region of faulting separating the inner continental shelf from the deeper parts of the basin (Modica and Brush, 2004). Generally speaking, a hinge line is thought to be a line separating stable crust from downwarped, extended curst. The trend of this 'hinge' is NE-SW, again following onshore basement trends (Light et al., 1992). See figure 2.12 for the hypothesised location of this structure.

In addition to the formation of lamprophyre dykes and syenitic plugs in the Serra do Mar during the post-rift period, magmatism also occurred in the offshore basin.

Dykes intruded through late Cretaceous sediments, feeding volcanic features and lava flows located in the east of the basin. These dykes are thought to have been influenced by the reactivation of basement features, and by the reactivation of older rift-related faults (Oreiro et al., 2008).

2.6 The West African margin

The conjugate continental margin to the Santos basin can be found in Angola and Namibia, in south-western Africa (Fig. 2.21). The Kwanza basin in the north, and the Namibe Basin to the south are both conjugate to the Santos basin. An understanding of how the rifting process affected these basins and the African margin in this region may help further our understanding of how the Brazilian margin formed, both during the Proterozoic and during the formation and evolution of the Atlantic.

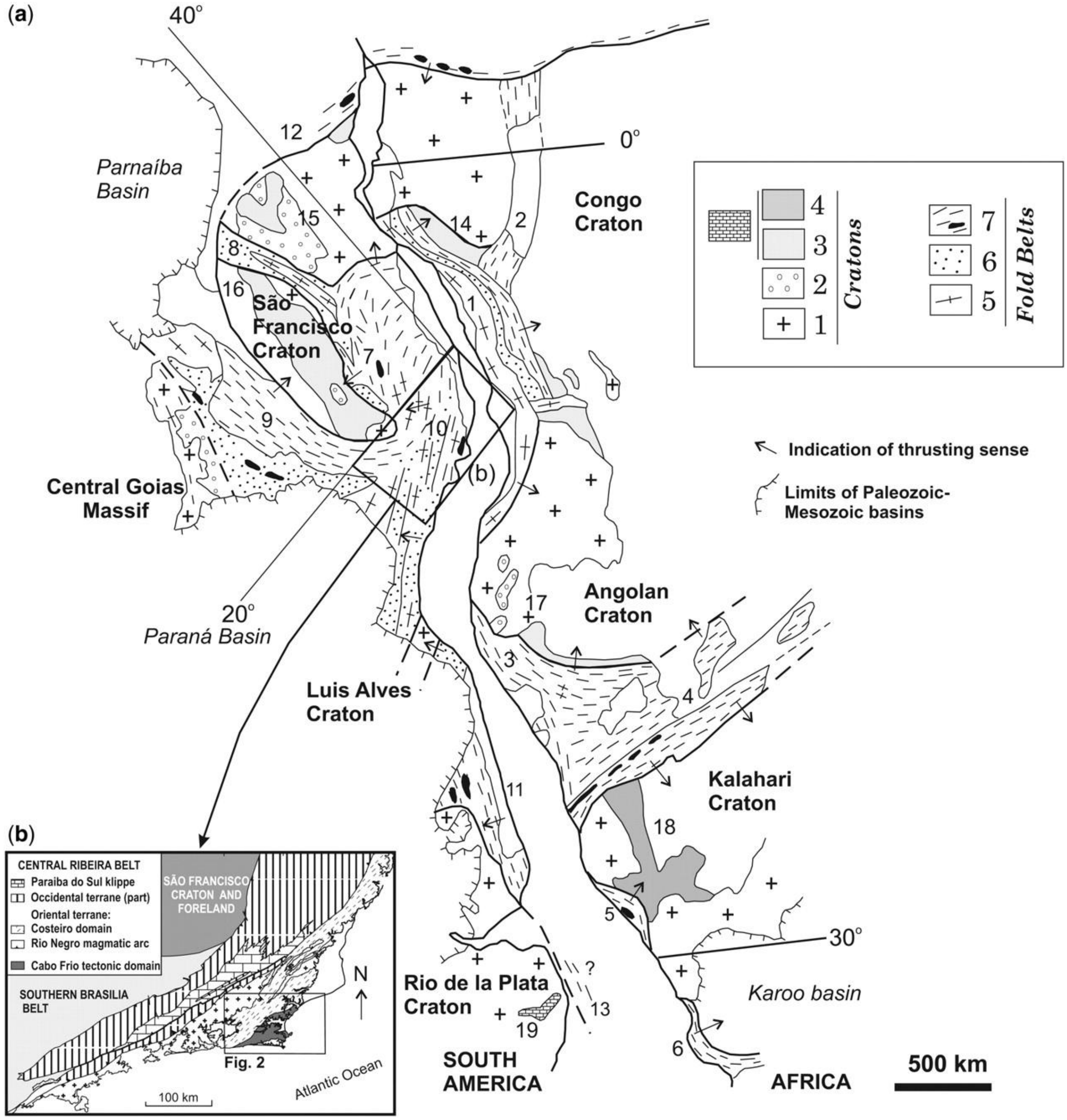


Figure 2.21 – Simplified geology of south-eastern Brazil and south-western Africa, restored to pre-rift configurations (Schmitt et al., 2008). 3 = the Kaoko belt, which correlates with the southern Ribeira belt and the Dom Feliciano belt. The Angolan craton forms much of the onshore region correlated with the northern Ribeira belt, although different units may underlie offshore basins.

Basement rocks on the African margin, like those on the Brazilian margin, consist of a series of orogenic belts formed during the Brasiliano (pan-African) orogen by the closure of oceans and the collision of cratons and cratonic fragments (Fuck et al., 2008). These were later faulted and uplifted as a result of the formation and evolution of the south Atlantic from the early Cretaceous to the present day. As with the Brazilian margin, basement rocks are thought to have influenced the development of rift-related and post-rift structures (Guiraud et al., 2010).

The Angola Craton is correlated with the São Francisco craton in South America (Fig. 2.6) with the two regions being part of a larger Craton, the Congo Craton (Fuck et al., 2008). The Ribeira, Araçuaí and Kaoko belts were formed during the closure of an embayment in this Craton during continental collision in the Brasiliano (pan-African) Orogeny (Cordani et al., 2003a). The Angola Craton was deformed in multiple events, dating from 2200Ma to 500Ma (Carvalho et al., 2000), and consists mainly of gneisses, granites and migmatites, intruded into more basic rocks such as gabbros and anorthosites (Carvalho et al., 2000). Structures (typically foliations) in the craton have a variety of trends, depending on the deformation period. Typically, structures in the craton trend N-S to NE-SW (Carvalho et al., 2000).

The Kaoko belt was formed around the southern and western edges of the Angola Craton (Fig. 2.6). It is a Neoproterozoic orogenic belt that has been correlated with the Ribeira belt. It forms the onshore basement to the Namibe basin, (Schmitt et al., 2008) and trends approximately N-S (Fig. 2.21), parallel to the continental margin (Goscombe et al., 2003). Structures in the belt largely consist of mylonitic, crustal scale shear zones (Fig. 2.22), formed by transpression during the Brasiliano (pan-African) orogeny (Goscombe et al., 2003). The Kaoko belt is considered to have formed from the accretion of several different units, representing the passive margin of the Angola craton, accreted during continental collision (Goscombe et al., 2003).

To the south, the Kaoko belt is covered by sedimentary and volcanic rocks of the Etendeka basin. Before rifting, this basin was originally part of the Paraná basin, and contains correlative lava flows and sediments (Peate, 1997) The evolution of the Paraná-Etendeka basin has been linked to the Tristan mantle plume, and the Walvis ridge and Rio Grande rise appear to show this hot-spot track after the onset of ocean spreading (White and McKenzie, 1989). Dykes associated with the Etendeka basin trend N-S, roughly parallel to the continental margin (Stewart et al., 1996)

To the north of the Etendeka province, rift-related faults have been observed in Angola trending N-S, with normal-sense offsets (Guiraud et al., 2010). These faults are segmented by NE-SW trending zones, which continue into the offshore basins (Guiraud et al., 2010). Faults further south in Namibia more typically trend NNW-SSE, roughly parallel to the coast (Stanistreet and Stollhofen, 1999).

From north to south, the Kwanza, Benguela and Namibe Basins lie offshore Angola and Namibia and correlate with the Santos basin, when pre-rift geometries are restored. The northern region of the Kwanza basin is thought to correlate with the Campos basin, and the southern part of the Namibe basin with the Pelotas basin (Mohriak and Rosendahl, 2003). The three basins are separated by basement highs. The Kwanza basin is separated from the Benguela basin by a seamount chain, and the Walvis ridge separates the Benguela and Namibe basins (Light et al., 1992; Schollnberger, 2001).

Whilst the Kwanza basin is relatively symmetrical with its conjugate – the Campos basin, the Benguela and Namibe basins are relatively narrow compared with the Santos basin, and the two regions are classified as a ‘wide-narrow’ margin pair (Reston, 2010). The causes for this wide-narrow contrast are not well understood, but are thought to relate to the obliquity of extension and the switch between ocean spreading in the Santos basin and the formation of the mid-Atlantic ridge (Davison, 1997; Reston, 2010; Scotchman et al., 2010). In contrast to the wide, highly extended Santos basin, these African marginal basins are characterized by major, large offset, syn-rift normal faults and a relatively abrupt continent ocean transition (Light et al., 1992). These syn-rift faults are thought to have resulted from the reactivation of basement structures during the early rift (Hudec and Jackson, 2002). The Kwanza and Benguela basins are segmented by ENE-SSW trending transfer zones, which were are thought to have later been reactivated in compression, possibly as a result of ridge-push (Hudec and Jackson, 2002).

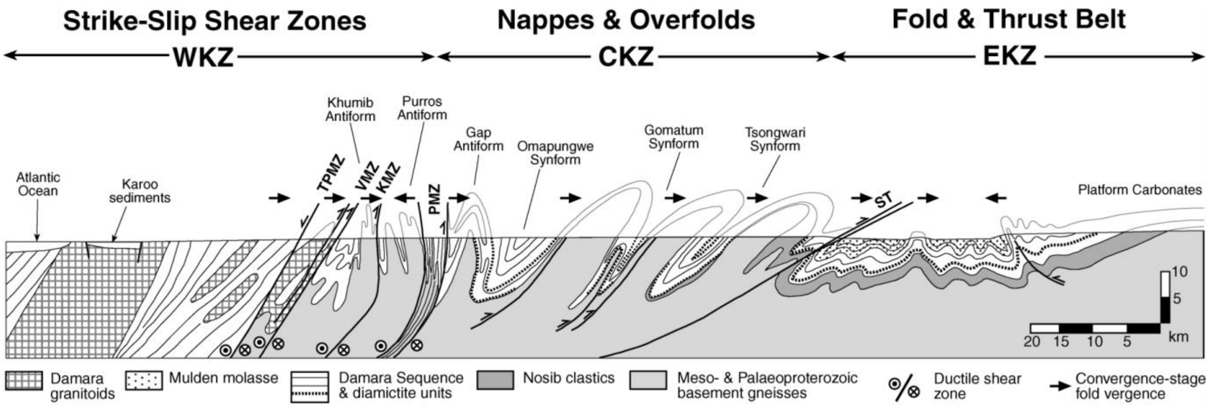


Figure 2.22 – Cross section through the Kaoko Belt in Namibia, illustrating its complex structure, consisting of zones of different styles of deformation, formed as a result of strain partitioning during transpression (Goscombe et al., 2003). Figure 2.9 shows a generalised cross-section through the Ribeira belt, and can be compared with this section.

Like the Santos basin, the basins on the West African margin have a 'hinge zone, outboard of which extensional deformation is concentrated. This hinge zone trends roughly N-S, parallel to the modern coastline, approximately 100km offshore. The hinge zone separates sediments that have been faulted and rotated in the offshore basin from relatively undeformed sediments and basement rocks in the near shore and onshore regions (Light et al., 1992).

Sedimentation in the basins is thought to predate the lower Cretaceous lava flows that are found in the Santos basin. The oldest sediments are thought to date from the Karoo basin, and are considered to be pre-rift (Light, 1992). Syn-rift sediments, like their Brazilian counterparts comprise lacustrine deposits and shallow water carbonates, covered by salt, and deposited during a period of regional sag (Davison, 2007; Light et al., 1992; Schollnberger, 2001). Lava flows, like the syn-rift lava flows in the Santos basin, have not been documented in the Kwanza or Benguela basins, but volcanic rocks and seaward dipping reflectors have been observed offshore Namibia (Abreu, 1998; Light et al., 1992). Salt tectonics in the Kwanza basin are thought to have been influenced by compressional reactivation of extensional faults, related to ridge-push (Hudec and Jackson, 2002). Following the deposition of salt, and the onset of ocean spreading in the mid-Atlantic, sedimentation was dominated by terrigenous sediment from the African margin (Anderson et al., 2000).

2.7 Brazil-Africa Correlations

Attempts to correlate South America and Africa date back to before the earliest days of the theory of continental drift (Rupke, 1970). More recently, attempts have been made to correlate the regions with greater accuracy, in order to improve understanding of processes related to both the Brasiliano (pan-African) orogeny, and Atlantic rifting (Moulin et al., 2010; Schmitt et al., 2008; Torsvik et al., 2009)

On a large scale, plate reconstructions have concentrated on the kinematics of continental breakup. These are based on the geometry of oceanic fracture zones and the location of the continent ocean boundary (Aslanian et al., 2009; Torsvik et al., 2009; Unternehr et al., 1988). Many of these models are based on dividing the south American and African continents into rigid blocks which move relative to each other (Aslanian et al., 2009). Timings are based on seafloor magnetic anomalies, and the stratigraphic development of offshore basins (Davison, 2007; Moulin et al., 2010). These models frequently show misfits such as gaps or overlaps between the continent ocean transitions of Brazil and Africa (Moulin et al., 2010), highlighting the need for onshore and offshore geological data to better constrain the reconstructions. A criticism of a number of these models is that the boundaries of many of the rigid blocks by which continents are divided are inconsistent with known geological structures, and that they do not account for distributed deformation within plates. Recent models have sought to address these problems (Johnson, 2012).

Since a significant amount of rifted continental crust is now found beneath the sediments of the Santos and Kwanza basins, correlations between the basement rocks of the two margins have proved problematic (Schmitt et al., 2008). The Cabo Frio terrane of the Ribeira belt is thought to extend beneath the offshore Santos basin, although its offshore extent is unknown, and it has not been correlated with any of the terranes in the Kaoko belt (Schmitt et al., 2008).   Similarly, the Florianopolis granite is not thought to correlate with any features in Angola or Namibia, as no granites of a similar age have been observed on the African margin (Basei et al., 2008).

Since many of the terranes of the Ribeira and Kaoko belts crop out onshore and inland, and trend parallel to the coastline, they may not be expected to correlate with structures on the African margin. Structural trends, timings of metamorphic and structural events, and the locations of the São Francisco and Congo cratons to the north of the Ribeira and Kaoko belts, however, do correlate well when south America and Africa are restored to their positions 125-135Ma (Schmitt et al., 2008; Trouw et al., 2000)

Igneous and volcanic rocks related to the Atlantic rift have been correlated across the south Atlantic. In particular, the Paraná and Etendeka basins have been shown to have been one larger basin (Peate, 1997). Furthermore, some authors have correlated the Ponta Grossa arch with the Moçâmedes arch in Angola. Whilst the Ponta Grossa arch consists of NW-SE orientated faults and tholeiitic dykes, the Moçâmedes arch is a region of carbonatitic magmatism roughly oriented NE-SW (Comin-Chiaramonti et al., 2008).

2.8 Conclusions

In order to understand potential influences on continental rifting, it is crucial to have an understanding of the geology of the region that was rifted. The Ribeira belt trends strongly NE-SW, and so could be an ideal candidate for basement reactivation and influence, as has been hypothesized by many authors. In addition, the apparent parallelism between structures offshore and those onshore supports a basement-influenced model for the development of structures in the Santos basin offshore. It is important, therefore, to consider individual basement structures and lithologies in order to fully understand if and how they may have influenced the development of later structures. The hypothesized presence of a mantle plume, with 3 dyke swarms forming a ‘triple junction’ supports an alternative model in which the development of the basin is strongly influenced by external factors, rather than basement being the dominant control. It is therefore important to consider that a variety of influences and controls may be responsible for the development of the margin (a major topic of this thesis). See chapter 3 for discussion of these potential influences and controls.

A consistent feature of the Ribeira belt is that basement structures trend parallel to post-rift brittle structures onshore and to syn-rift structures offshore. Given the E-W extension direction predicted from Atlantic spreading vectors, this could have resulted in the development of an oblique rift. The implications of oblique deformation, together with the many different potential influences on rift development will be discussed in the next chapter. Remotely sensed, field, and offshore data that were collected to test these hypotheses are presented in chapters 4, 5, and 6.

3 Oblique tectonics and Continental rifting

3.1 Introduction

The margins of the south Atlantic display a large amount of diversity in both their orientation and structural style. The cause of this variation along the length of the continental margin is not well understood. Margin orientation and structural style has a strong influence on the development of sedimentary basins, in terms of their structural development, geometry, and fill history. It is also a fundamental control on hydrocarbon prospectivity.

Margins form as orthogonal, oblique and transform segments. An orthogonal margin segment is one which forms at close to 90° to the regional extension (ocean opening) direction. These margin segments are characterised by dip-slip normal faults. By contrast, a transform margin forms at a low angle to regional extension vectors, and its development involves a predominance of high offset strike-slip faulting. An oblique margin develops at angles between 0° and 90° to regional extension, and features components of both orthogonal and transform rifting. This combination of dip-slip and strike-slip deformation is called transtension (Dewey et al., 1998; Withjack and Jamison, 1986). Based on its orientation relative to regional extension vectors, the Santos Basin (chapter 2.2) can be considered an obliquely rifted margin, and therefore transtensional deformation may have occurred during its early evolution.

An appreciation of the styles and controls of transtension in continental rifting is clearly important in order to understand the development of oblique margin segments during continental separation, and the associated development of sedimentary basins.

3.2 Oblique Tectonics

Faults form and develop by brittle failure in the upper crust in response to regional and local stresses. In classical Andersonian faulting, conjugate faults form oriented at 30° to the direction of the maximum principal compressive stress, $\sigma1$, and intersect parallel to the direction of the intermediate stress direction, $\sigma2$ (Anderson, 1951). In general, one of the principal stress directions must lie normal to the surface of the Earth as this is a surface of zero shear stress (ignoring the effect of surface topography). Thus three end member stress regimes and conjugate faulting patterns are recognized: normal or extensional ($\sigma1$ vertical), reverse or compressional (σ3 vertical) and strike-slip (σ2 vertical) (Fig. 3.2). Such Andersonian conjugate faulting produces a symmetrical pure shear deformation which is also a two-dimensional plane strain (Twiss & Moores 2007). This means that the total deformation can be described in a single plane – such as a cross-section - oriented at 90º to the σ2 direction. The deformation in such cases is coaxial meaning that stress and finite strain axes remain fixed and sub-parallel during the entire deformation.

Natural deformation patterns are rarely this straightforward. The development of tectonic plates on a spherical Earth mean that most margins experience relative displacements and strain that are significantly oblique – this leads to a regional component of shear strain and structural asymmetry. In its simplest form, a simple shear (Fig. 3.1)., the resulting deformation is also a plane strain that can involve sets of conjugate Andersonian shear fractures that form markedly oblique to the deformation zone margins. The axes of finite strain (and their resultant structures) rotate leading to an asymmetric non-coaxial pattern of deformation; so that stress and strain axes are now no longer parallel. In simple shear zones where there is a component of shortening (transpression) or extension (transtension) across the regional of deformation, the resulting stain is no longer plane strain and all three stress and strain axes are non-parallel and may rotate as deformation progresses

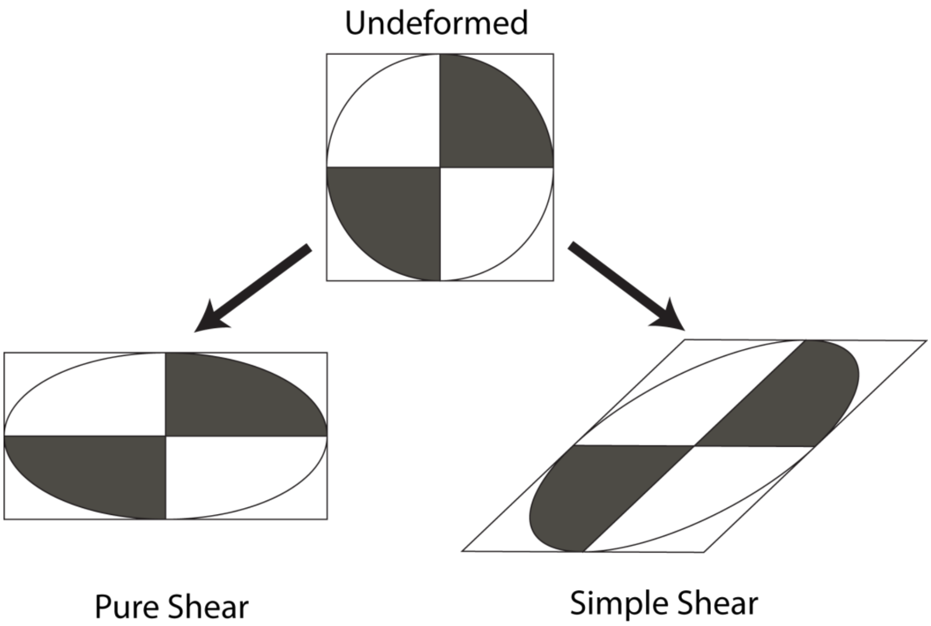


Figure 3.1 - Pure shear and simple shear.

According to the simple Andersonian relationship between regional stresses and fault development, a rift formed by east-west extension would be expected to be formed from N-S trending normal faults. In many settings however, this orthogonal relationship breaks down. The angle between the rift trend and the extension direction has been ascribed the symbol ‘α’ (Clifton et al., 2000). As the angle α decreases, the rift is said to become more oblique and transtensional. A transtensional rift with values of α between 90° and 20° is considered ‘extension-dominated’, whereas values of α less than 20° are considered ‘wrench-dominated’ (Fig. 3.4). Structures in extension dominated settings are more likely to consist of dip-slip or oblique-slip normal faults, whereas strike-slip faults are more likely to dominate in a wrench dominated setting (De Paola et al., 2005; Teyssier and Tikoff, 1999).

As faults develop obliquely to regional extension vectors, they no longer form parallel to regional $\sigma 2$. A conventional 2-dimensional Andersonian model can no longer be assumed. Faults forming in a 3-dimensional, non-coaxial stress field form under the influence of all 3 principal stresses, and can therefore form more complex geometries (Krantz, 1989; Reches and Dieterich, 1983).

These 'non-andersonian' faults typically form 2 or more conjugate fault sets, whereas Andersonian faulting forms only one. These fault sets often form an orthorhombic pattern (Fig. 3.5), and are typically termed ‘quadrimodal’ (Andersonian faulting is ‘bimodal’)(Aydin and Reches, 1982). Quadrimodal – or more generally multimodal faults form simultaneously and all faults are therefore mutually cross-cutting. Field identification and interpretation of multiple fault sets are therefore important in order to distinguish between faults formed from multimodal event and multiple fault sets formed during different events (Nieto-Samaniego and Alaniz-Alvarez, 1995). These will show mutual cross-cutting as opposed to systematic cross-cutting relative age relationships, respectively. A further complication factor is that the presence of pre-existing weaknesses can significantly affect how such faults develop and evolve (Nieto-Samaniego and Alaniz-Alvarez, 1995).

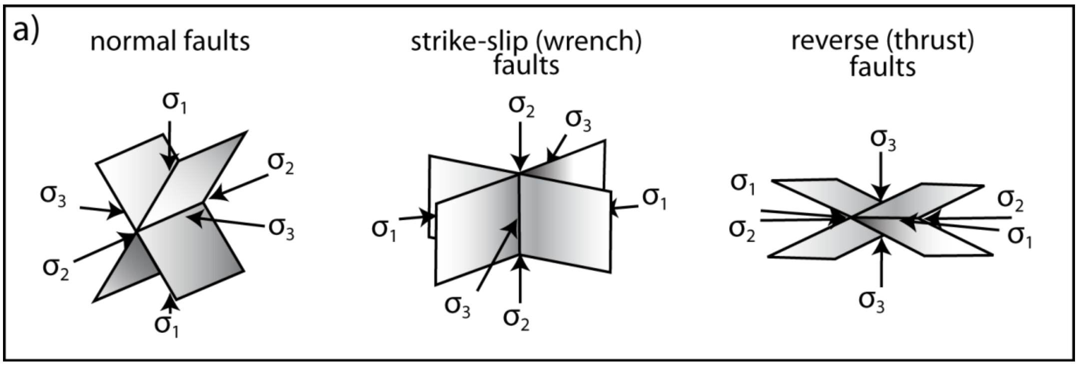


Figure 3.2 – Types of faults, and their orientation relative to principal stresses. modified from McClay (1991).

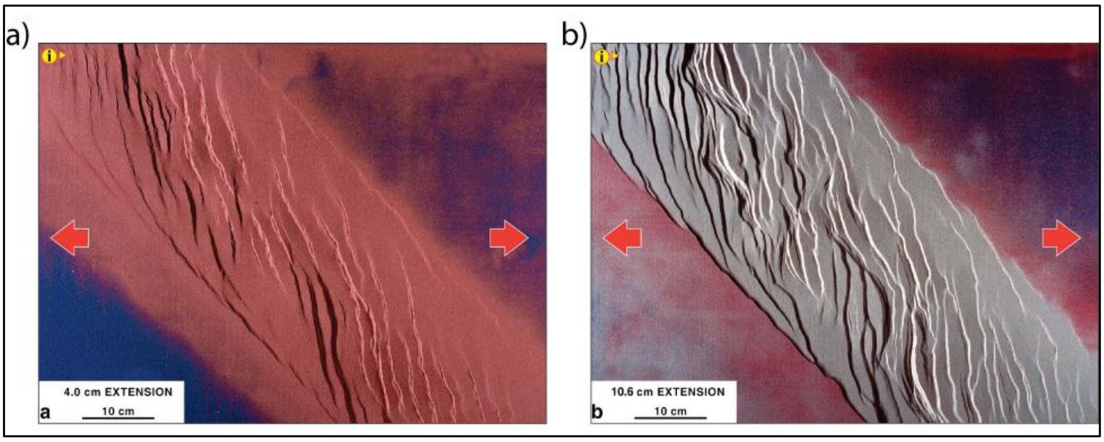


Figure 3.3 – Analogue models of oblique rifting, at α = 45°. As rifting progresses, faults in the rift appear to form at 90° to the extension direction, whilst transfer zones, parallel to the rift margins form (McClay et al., 2002).

In strike-slip and wrench-dominated transtensional settings, the principle directions of tectonic extension (parallel to σ3) and compression (parallel to σ1) both lie in the horizontal plane so that normal faults together with thrust faults and folds, can form simultaneously at low and high angles to the rift trend, respectively (Fig. 3.6) (Teyssier and Tikoff, 1999).

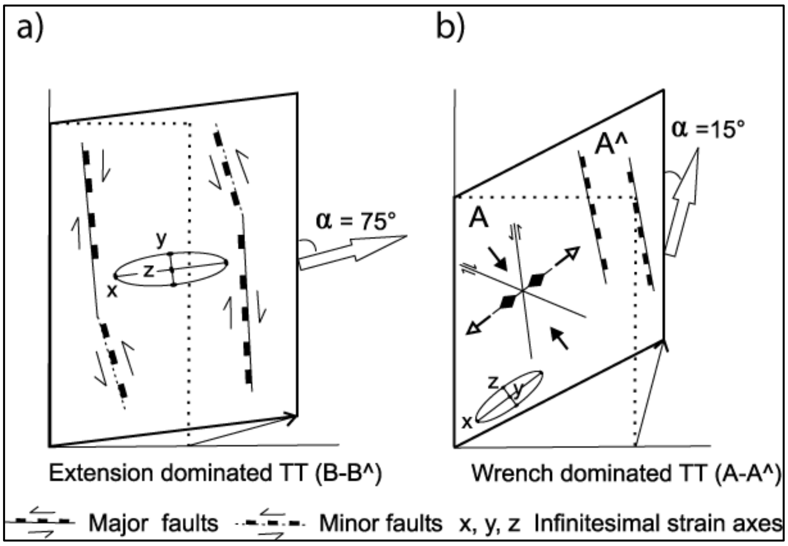


Figure 3.4 – Structures formed in extension dominated (a), and wrench dominated (b) transtension. In an extension dominated setting, normal and oblique extensional faults dominate. As the region becomes increasingly wrench dominated, whilst normal faults can form, strike-slip structures, and even compressional structures can also form, in response to the horizontal shortening component of the strain (De Paola et al., 2005).

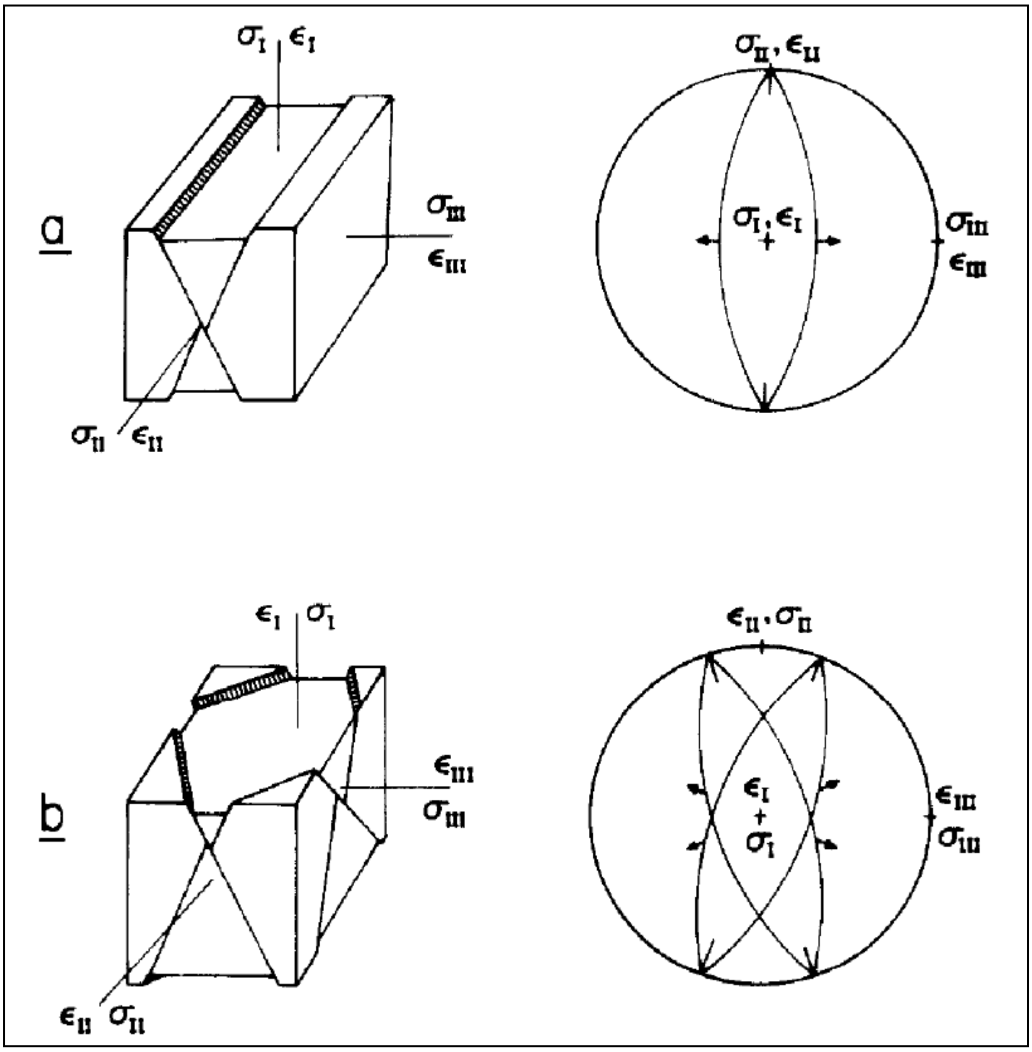


Figure 3.5 – Comparison between Andersonian (a), and polymodal faulting (b) (Reches, 1983). Note the mutual cross-cutting relationships of the faults in part b.

Dewey et al. (2008), among others (e.g. De Paola et al., 2005) showed how transtensional and transpressional deformation can result in the partitioning of strain into more wrench-dominated, and more extension-dominated domains. This partitioning has the effect of splitting the strain into individual 'plane strain' components, leading to smaller regions of wrench-dominated transtension and extension-dominated transtension within the larger deforming region. One reason for this partitioning may be the incompatibility of local strains over a large area. Rocks several hundred kilometers apart may respond differently to the same regional forces. This partitioning is typically related to the reactivation of pre-existing basement structures (De Paola et al., 2005; Dewey et al., 1998).

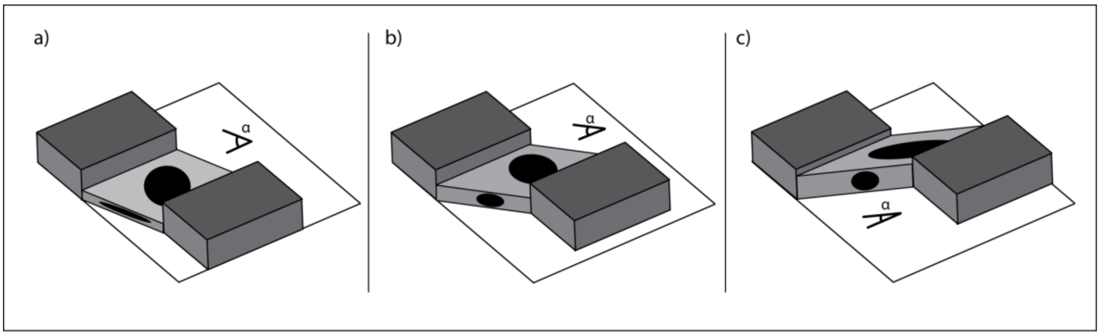


Figure 3.6 – Transtension and shortening. As the angle α decreases, the rift becomes increasingly wrench-dominated. In an extension-dominated setting (a), shortening is vertically oriented, whereas in a wrench dominated system (c), shortening is horizontal, leading to the formation of compressional structures. Based on Teyssier and Tikoff (1989).

Whilst no volume change during deformation may be assumed in some settings, it is important to consider how the addition of volume to the crust can affect a transtensional rift. In the case of the Brazilian margin, dykes were intruded before, during and after rifting and will have had a significant influence on the development of the margin (Guedes et al., 2005). The formation of a dyke swarm can lead to a significant volume increase and tectonic strain that is kinematically equivalent to an orthogonal extension. Thus in a given region undergoing transtension, dyke intrusion can help to accommodate margin-normal extension leaving more of the shear component to be accommodated by deformation in the surrounding country rocks. The more volume is added, the more of the extensional component can be accommodated, and therefore the more likely faults and fabrics are to be wrench dominated (Teyssier and Tikoff, 1999).

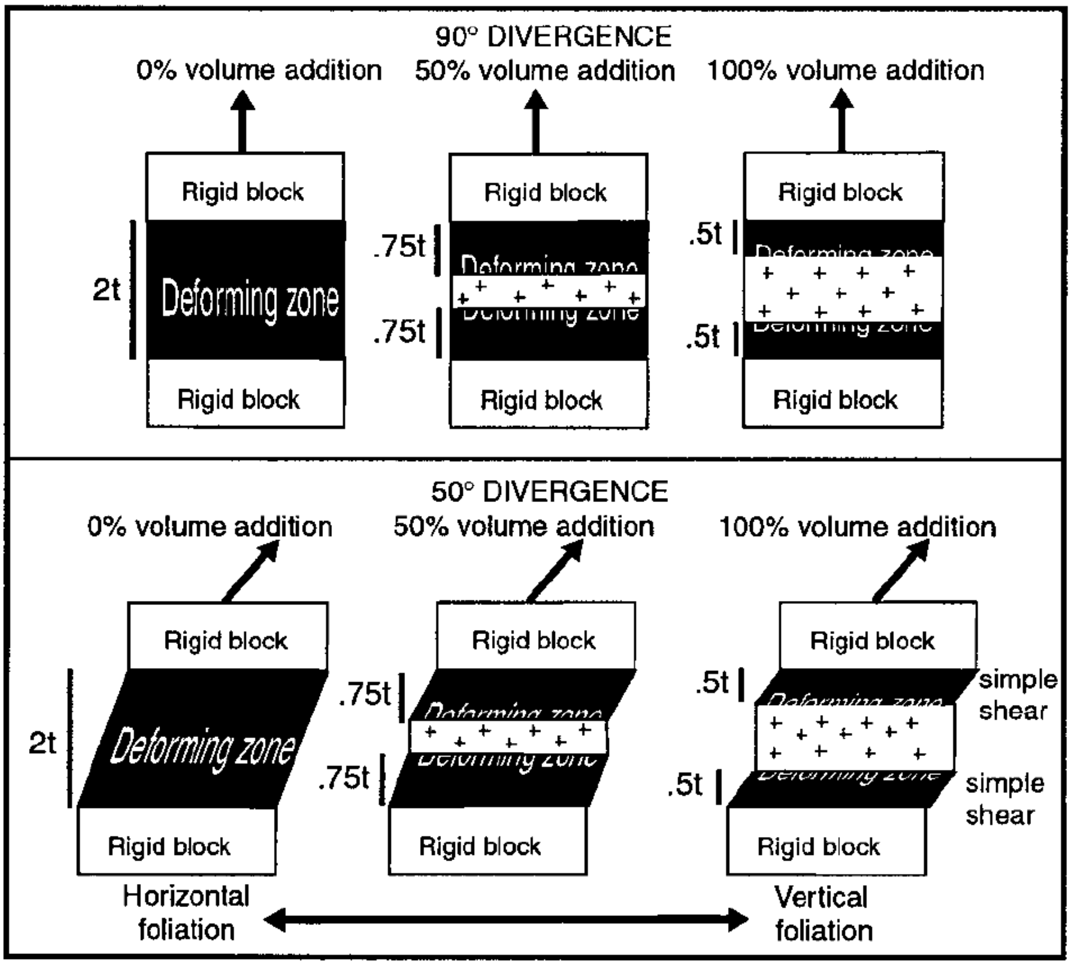


Figure 3.7 – Volume addition during transtension. The deforming region has an initial width 't' As volume is added into a transtensional system (bottom of diagram), deformation focuses on refines with smaller values of 't'. Deforming regions therefore become more wrench dominated in order to accommodate the oblique component of extension. (Teyssier and Tikoff, 1999).

3.2.1 Why are rifts oblique?

Many rifts are oblique as an inevitable complex of plate tectonics occurring on the surface of a spherical planet – relative plate motions and the regional stresses that result are more often than not significantly oblique both in the present day and in the past (Dewey 1981; Woodcock 1986). To this may be added the fact that most plate margins have complex curvilinear shapes and that pre-existing structures – which often significantly control the orientation of structures formed during rifting - are often oriented significantly oblique to the far-field regional tectonic movement vectors (Dewey et al. 1998, 2002).

3.2.1.1 Oblique fault geometries

Since they form in coaxial, plane-strain conditions, typical Andersonian faults display either dip-slip or strike-slip kinematics. By deforming obliquely, faults accommodate both strike-slip and dip-slip deformations. If reactivated, pre-existing heterogeneities trending at angles other than 0° or 90° to the extension direction are likely to form as oblique faults (Bott, 1959) Non-plane strain deformation can also result in the formation of oblique slip faults (Reches, 1978).

Faults that form in oblique settings often display features typical of both strike slip and normal fault systems. Depending on the orientation of regional and local stresses, they can also exhibit compressional features (Withjack and Jamison, 1986). Structures such as oblique slip faults and polymodal fault populations are common, as are structures more commonly associated with strike slip settings, such as Riedel shears and pull-apart basins (Sylvester, 1988).

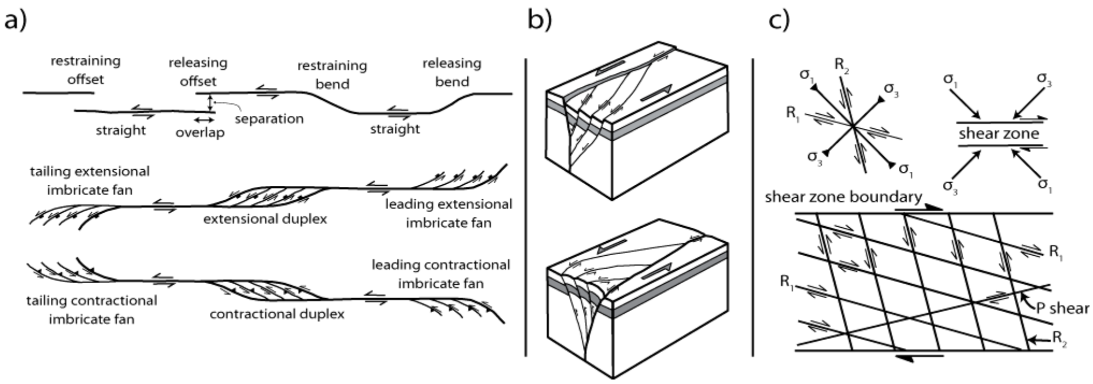


Figure 3.8 – Structures formed in strike slip settings. These structures can often be found in regions which have undergone transtension, in addition to those which have undergone purely strike-slip deformation. a) Restraining and releasing bends form where the fault changes direction. The geometry of these bends relative to regional stresses can affect whether local structures are extensional or compressional. Modified from Woodcock and Fischer (1986) b) "Flower structures" formed as a result of oblique extension (top), or compression (bottom), where smaller structures link to larger faults (Woodcock and Fischer, 1986). c) Riedel shears form complex geometries in response to strike-slip deformation. Modified from McClay (1991) These structures can be formed at a variety of scales, from small scale microfractures within localised shear zones, to large regional scale structures e.g. Tchalenko (1970).

Differentiating between faults which have oblique offset and those with pure dip-slip or strike-slip offset requires the use of kinematic indicators such as slickensides and steps on a fault surface (Fig 3.8), offset indicators, such as crosscut veins or bed boundaries which show both vertical and horizontal offset, or the recognition of geometries such as splays, bends and branches in the fault or fracture itself.

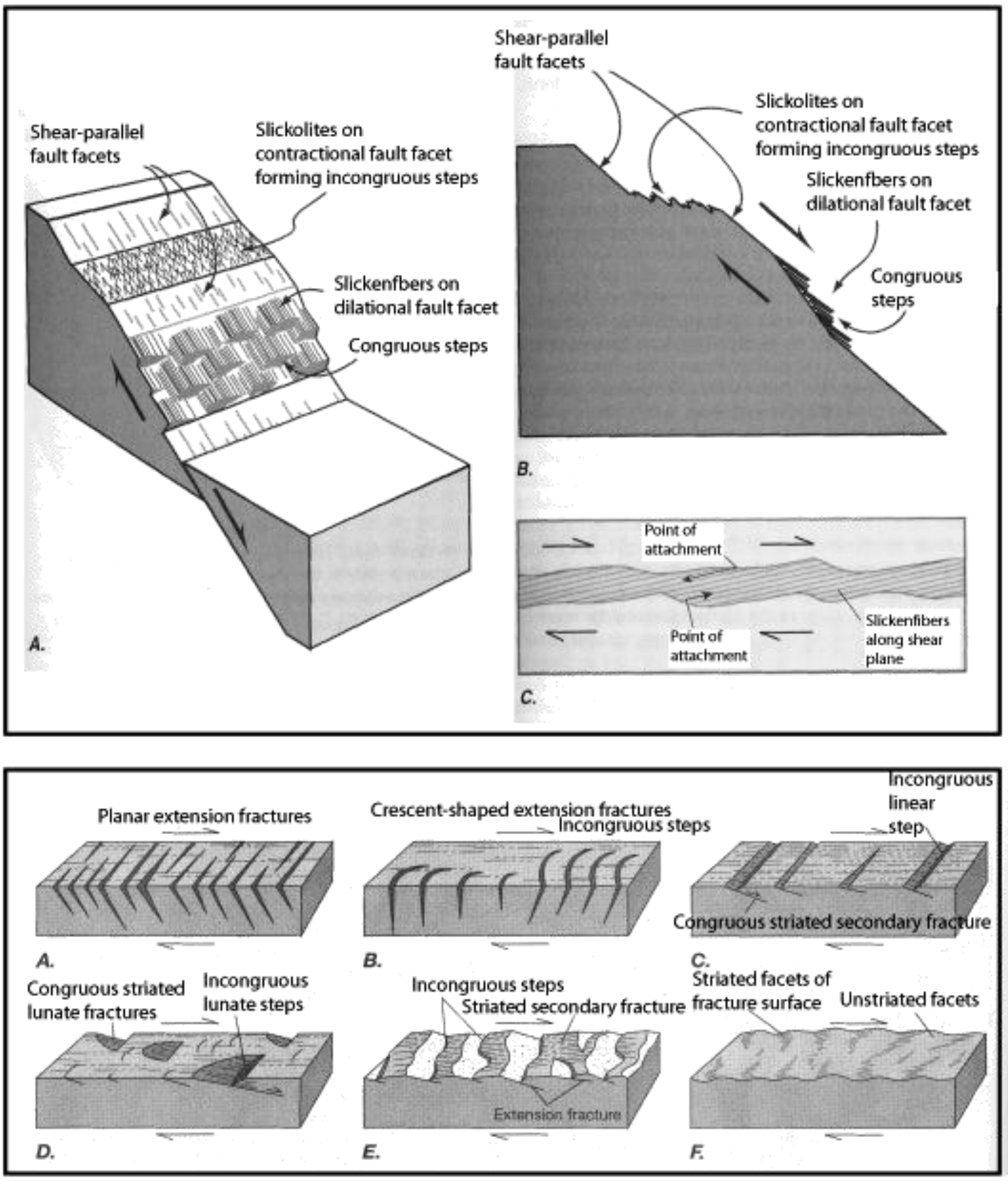


Figure 3.9 – slip sense indicators on faults. Modified from Twiss and Moores (2007).

3.2.1.2 Timing of fault and fracture generation

Identification of the timings of fault generation and activity depends primarily on relative observations of cross-cutting relationships. Where a fault containing fault rock crosscuts another structure, it is possible to identify the age relationship. Similarly, if a structure consistently offsets other structures by the same amount, and ideally where it also offsets basement fabrics and structures by this amount, it gives a reliable age relationship. Complexity arises where faults do not appear to offset with consistent kinematics, or where one structure appears to offset older structures by different amounts. In addition to these complexities, since extensional fractures terminate against one another (abutting relationships), any apparent cross-cutting relationships may be misleading. See Twiss and Moores (2007), pp54-55 for a more detailed discussion of timings of fracture generation.

3.2.2 Basement influence and reactivation

The role of pre-existing fabrics and structures in the evolution of continental rifts has been discussed since the development of plate tectonic theory (Wilson, 1966). Structures, formed during previous tectonic events may be reactivated during rifting, or their location, strength and spacing may influence the development of later structures (Holdsworth et al., 1997; Morley et al., 2004). The scale of these structures may vary from crustal-scale shear zones or faults to small scale fabrics such as foliation or bedding. In the case of the Atlantic rift in south-eastern Brazil, prior to the development of rift-related structures, the dominant pre-existing fabrics and structures were foliations and shear zones of the Ribeira belt, formed during the Brasiliano orogeny.

3.2.2.1 Influence or reactivation?

It is crucial when dealing with the role of basement geology in brittle tectonics to define ‘basement influence’ versus ‘basement reactivation’, as they may have different implications for the way in which faults have developed and evolved. For basement reactivation, pre-existing basement structures must be directly reactivated e.g. faults along pre-existing structures, as a result of the structures being easier to fault than surrounding rocks (Holdsworth et al., 1997). In this study, I use ‘basement influence’ as a more general term, which does not imply reactivation, although this can occur in a basement-influenced setting. Relative strengths due to different rheologies or variations in fabric intensity between different locations may have a strong influence on the development of later faults and fractures without structures being directly reactivated. A good example of this can be seen in the east African rift, where large scale differences in mechanical strength between cratonic basement and orogenic belt basement resulted in deformation being focused in the ‘weaker’ orogenic belts (Smith and Mosley, 1993)

Another often used term is 'basement inheritance' eg. Cortes et al (2003). This term is often used interchangeably with basement reactivation, implying that older structural trends are inherited by younger structures). The term is also often used to describe basement influence, where no evidence for direct reactivation can be found (eg. Cortes et al, (2003), among numerous other authors). ‘Reworking’ is a further term, defined by Holdsworth et al (2001), and used to describe large scale reactivation within the lower crust (Fig. 3.15).

In this study, when referring to ’basement’, I do not draw a distinction between upper and lower crustal deformation, or even crust and mantle. Instead, I use the term ‘basement’ to describe any crystalline rocks which were present at any crustal level, prior to the onset of later brittle deformation (e.g. Figure 3.15). The term ‘basement influence’ is used when discussing if and how these pre-existing crystalline rocks may have affected structures which formed during rifting.

For consistency, I will use the terms 'basement reactivation' and 'basement influence’ throughout this thesis, as described in the paragraph above.

3.2.2.2 Basement Reactivation

The way in which basement structures affect the development of younger brittle structures can depend on a number of factors. The strength, spacing, orientation, and size of basement structures can all influence the way in which later faults develop. See Figure 3.10 for an illustration of different criteria for recognizing basement reactivation.

3.2.2.2.1 Reactivation angles

Whether faults are reactivated depends on the mechanical strength of the fault, and its orientation relative to local and regional stresses. Many factors can affect the strength of both faults and rocks in general, and these are discussed in section 3.2.2.3. The most important factor relating to this strength is the contrast between the mechanical strength of the pre-existing structure and the strength of the rocks around it. If the country rock is easier (or) as easy to fault as the pre-existing structure, the structure is unlikely to be reactivated (Sibson, 1985).

The angle at which reactivation takes place is also fundamental to whether a heterogeneity will be reactivated. As the angle between the trend of the heterogeneity decreases, the lower the friction coefficient across the heterogeneity must be if the fault is to reactivate (Sibson, 1985). Typically, normal faults are most likely to reactivate at around 60° to the minimum principal compressive stress

(Sibson, 1985). In a number of natural cases, however, large faults have been known to reactivate at significantly lower angles to regional stresses, such as low angle normal faults such as the Zuccale Fault (Smith and Faulkner, 2010), and strike slip structures such as the San Andreas fault (Zoback et al., 1987). Structures which deform at such angles to regional stresses are typically considered to be very weak, often as a result of the mineralogy of the fault rocks present (Holdsworth et al., 2011; Smith and Faulkner, 2010).

3.2.2.3 What affects the strength of rocks?

A variety of factors may modify the strength of rocks, although the dominant causes of weakening relate to the mineralogy and structure of the fault rock, and processes which have affected its composition after formation, such as retrograde mineral growth or alteration by hydrous fluids (Imber et al., 1997). Primary processes affecting the strength may be grain size reduction, preferred mineral orientations, and the replacement of 'strong' minerals, such as feldspars, with 'weaker' minerals such as mica. Processes which affect the strength of rock on retrogression involve fluids, and the development of hydrous minerals such as phyllosilicates, and the weakening of silicates, especially quartz by hydrolytic weakening (Passchier and Trouw, 2005).

In addition to their strength and orientation, the spacing and size of pre-existing weaknesses can also affect the way later brittle faults can develop (Fig. 3.13). Discrete weak zones in the basement may lead to later brittle deformation being concentrated within and along basement structures, with little brittle deformation in between, whereas fractures influenced by highly pervasive basement fabrics are more likely to be spread more evenly across an area (Morley et al, 2004). Furthermore, in regions of discrete basement weaknesses, orthogonal deformation may be more likely to dominate between the weak basement structures, whereas oblique faults are likely to be more common across the area where basement weaknesses are pervasive (Morley et al., 2004).

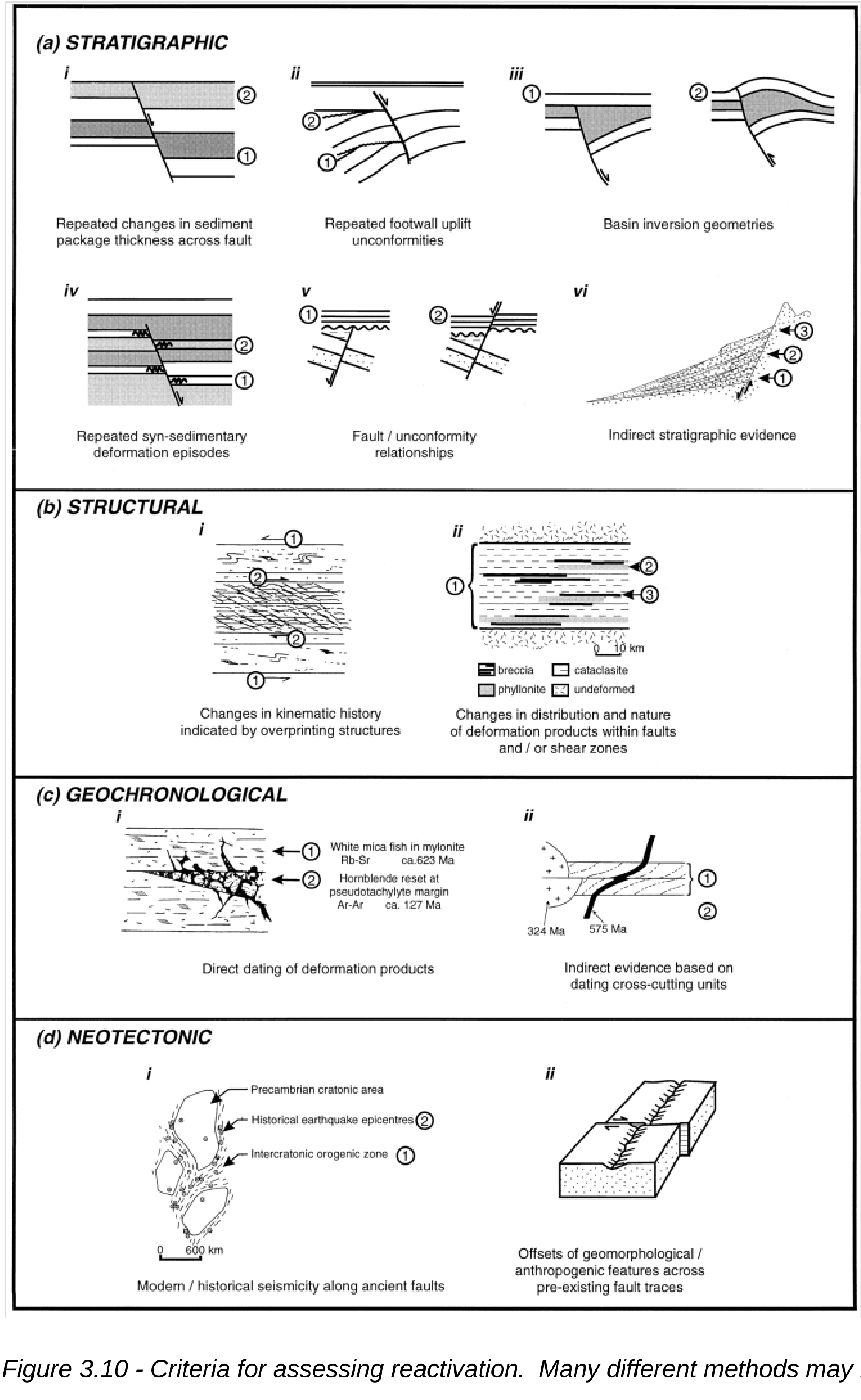


Figure 3.10 - Criteria for assessing reactivation. Many different methods may be used in order to identify whether or not a structure has been reactivated. In order to recognise ancient reactivation events, an understanding of the structure and stratigraphy of the fault and region being affected is essential (Holdsworth et al., 1997).

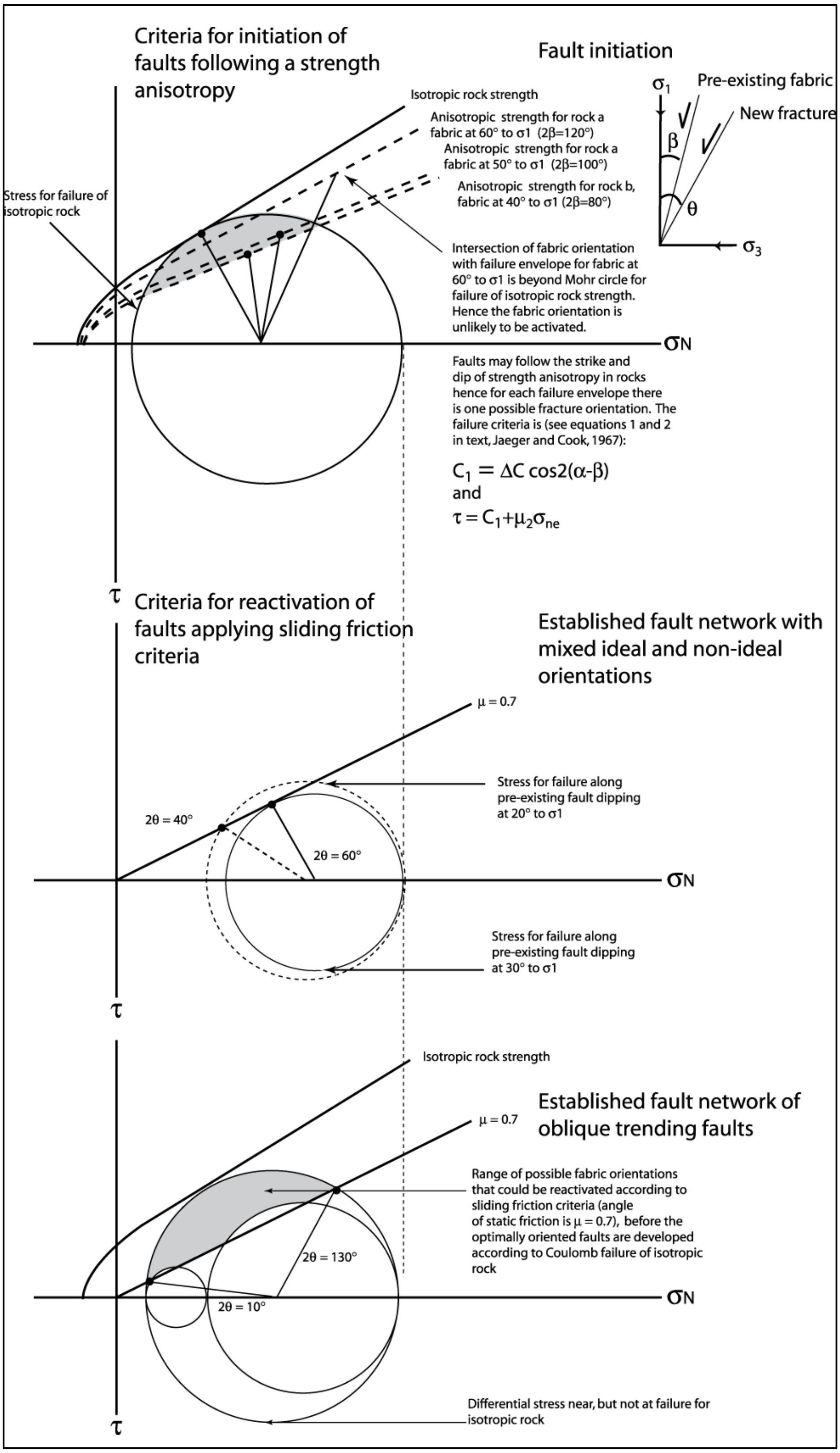


Figure 3.13 – Failure of a rock with pre-existing anisotropies will be more likely if the anisotropy is weaker than the bulk rock, and if the anisotropy is oriented correctly relative to regional stresses (Morley et al., 2004).

3.2.3 Basement influence

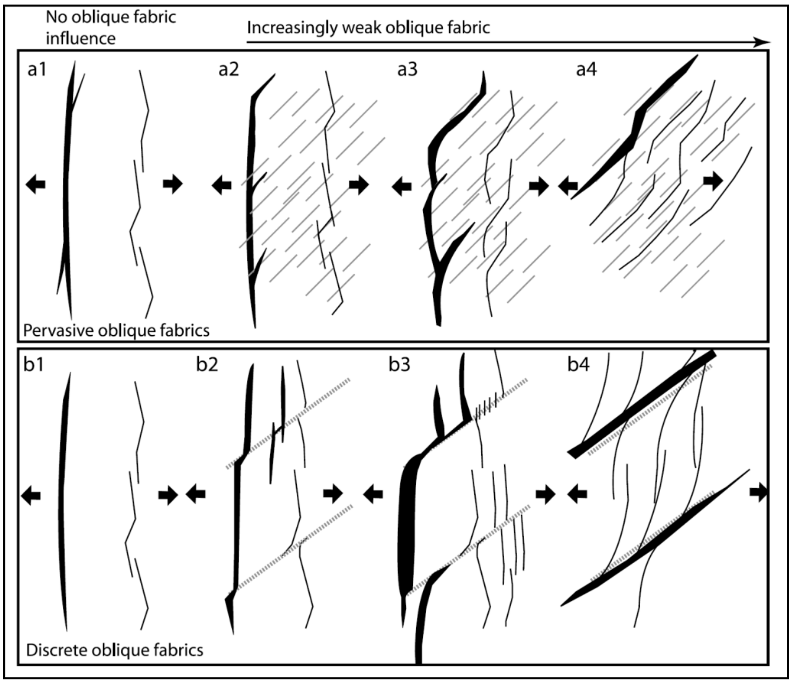


Figure 3.14 – The influence weak basement fabrics can have on the development of later brittle structures (Morley et al., 2004). In addition to the strength of the fabric, which can affect the geometries of faults, the pervasiveness of basement fabrics can also play a role in the later distribution of brittle deformation.

3.2.3.1 Lithospheric scale influences

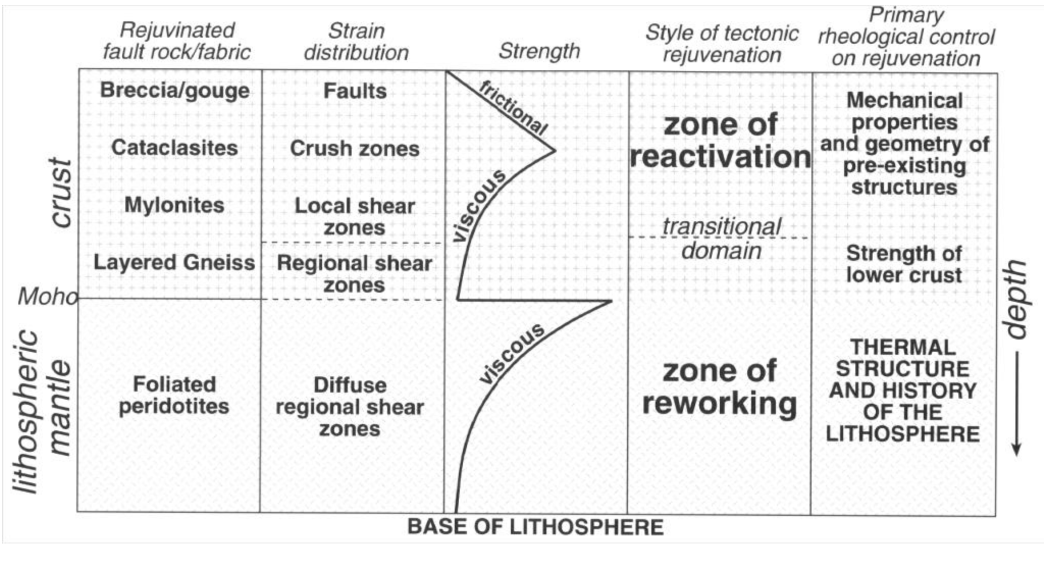


Figure 3.15 – Typical fabrics and structures responsible for reactivation and reworking (Holdsworth et al., 2001). The strength of the lithosphere (partly a function of its temperature) is a fundamental control on the structures which form,

and a control on how and where reactivation or reworking is likely to occur on a lithospheric scale.

Differences in lithospheric thickness between cratonic regions and orogenic belts are known to affect the location of rifts. Cratonic regions consist of thick, old, cold lithosphere, whereas orogenic belts are younger and weaker. Weak lithosphere at depth will have reduced yield strength due to higher temperatures (Fig. 3.15), and is therefore potentially easier to rift (Lynch and Morgan, 1987). Cratonic regions, on the other hand, have higher yield strengths as a result of lower temperatures. Preferentially thin young lithosphere may also be more likely to rift, as hotter mantle material is found at a shallow depth, reducing its strength relative to adjacent regions. Plume material may also pool in areas of thin lithosphere, again affecting subsequent rifting, e.g. Shervais and Hanan (2008).

Fabrics within the lower crust and upper mantle can control the location and structural style of rifts without brittle reactivation of basement faults in the upper crust. (Tommasi et al, 2009) Pre-existing features related to past tectonic events can have a strong impact on the development and localisation of rifts (Fig. 3.15). Regional scale shear zones and other large structures (up to orogenic belt scale) are likely to play an important role on focusing deformation (Holdsworth et al., 2001). Olivine is a significant mineralogical constituent of the upper mantle. During orogeny, fabrics are formed by the alignment of olivine crystals, caused by deformation by dislocation creep. The structure of olivine significantly affects the way in which it will deform (with most slip taking place along the weak slip system), leading to anisotropies in the upper mantle where the weak slip systems of olivine crystals are aligned parallel to one another (Durham and Goetze, 1977). Olivine crystals may deform up to 100 times faster along their weak slip systems than in other directions (Durham and Goetze, 1977; Tommasi et al., 2009)

If these anisotropies are preserved, they may control the development of later rifting. Regional stresses, depending on their orientation relative to olivine crystal anisotropy in the upper mantle, may be significantly more likely to reactivate the olivine along its weak slip system than they are across it (Fig. 3.14), which may lead to rifts being oriented obliquely to regional extension vectors (Tommasi et al., 2009).

Whilst these anisotropies may be likely to trend parallel to structures in orogenic belts, their presence is difficult to test, due to the difficulties of imaging the lower crust and upper mantle at high resolutions. Whilst the model has been proven theoretically, it is difficult to know whether or not anisotropies are present in the mantle, or whether they have been reactivated. Shear wave splitting is a useful tool to study the orientation of structures in the lower crust and upper mantle. Beneath the Ribeira belt, shear wave splitting has shown NE-SW trending anisotropy (Fig. 3.15), though the age of this fabric, and whether or not this fabric has affected rifting is unclear (Heintz et al., 2003).

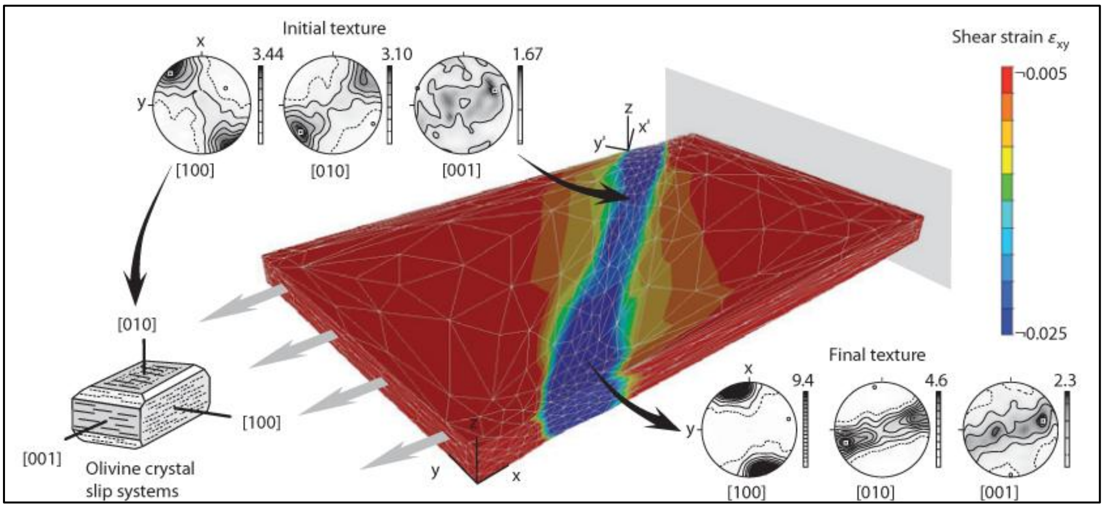


Figure 3.16 – The orientation of slip surfaces within olivine crystals can affect the location of rifts. This strain localisation (the blue region in the figure) can also affect the orientation of olivines further, leading to an increase in strain localisation.

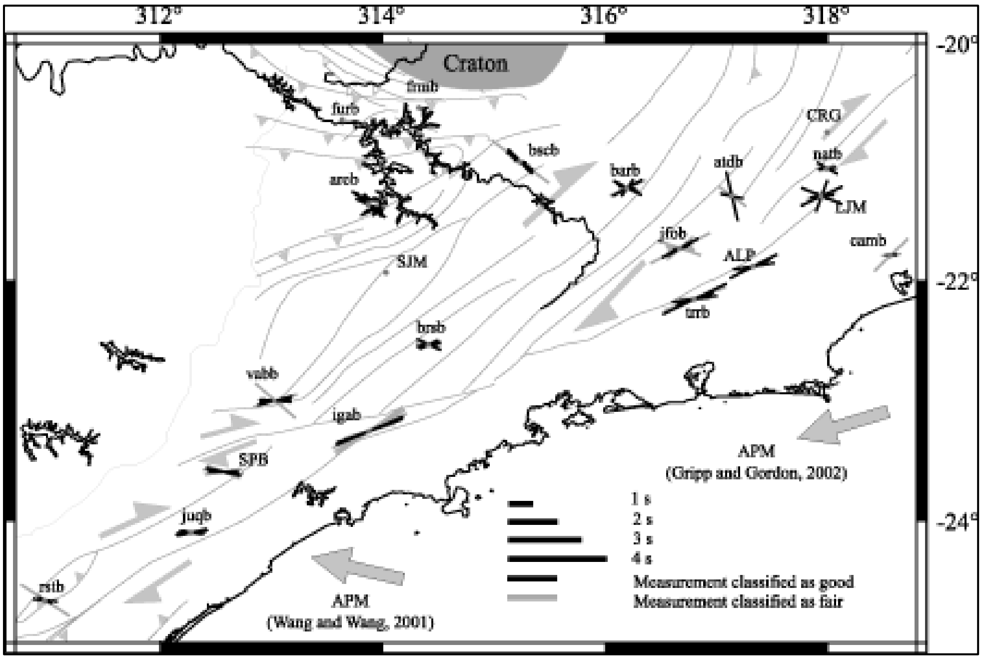


Figure 3.17 – The orientation of anisotropy beneath the Ribeira belt, from shear wave splitting studies (Assumpcao et al., 2006). The dominant direction is clearly parallel or sub-parallel to that of the Ribeira belt, possibly due to an orogenic fabric which may have been influential during rifting.

The thermal and rheological properties of the upper mantle are thought to play a large role in determining the structural style of an evolving continental rift. Hot mantle has a lower viscosity than cold mantle, and therefore deforms more easily in response to being stressed. This has the effect of creating wider, more diffuse rifts, in comparison to cool mantle, above which narrower rifts are more likely to form. Wider, hot rifts, however are less likely to progress to breakup than cooler rifts (Gueydan et al., 2008).

The presence of mantle plumes can also significantly affect how and where continental rifts develop (Burke and Dewey, 1973). Mantle plumes are buoyant regions of hot mantle which ascend due to their increased temperature making them more buoyant than the surrounding mantle (Morgan, 1972). As these plumes reach the base of the lithosphere, the increase in temperature can lead to melting and large amounts of volcanism. The increase in the temperature of the upper mantle can also lead to buoyancy, which can lead to regional doming (Morgan, 1972). In south-eastern Brazil, the presence of the flood basalts of the Paraná basin, drainage patterns, regional uplift, and the presence of the conjugate Rio Grande rise and Walvis ridge are all cited as evidence for a mantle plume having influenced rifting (O'Connor and Duncan, 1990; Thompson and Gibson, 1991).

Thermal domes have been observed in active rifts such as the east African rift, and are thought to be the result of mantle plumes at the base of the crust (Ebinger and Sleep, 1998). Dykes and rifts are thought to localise on thermal domes, forming triple junctions with their centre located above the centre of the plume head (Burke and Dewey, 1973).

3.2.3.2 Crustal scale influences

Crustal scale shear zones may be reactivated at depth, controlling the location and trend of faults at the Earth's surface. Both steeply dipping and shallowly dipping structures can be reactivated, with steeply dipping basement structures thought to be responsible for the location of strike-slip faults and transfer zones, and shallow dipping structures responsible for the locations of low angle detachment faults (Fig. 3.16). (Daly et al., 1989; Morley et al., 2004; Moustafa, 1997; Smith and Mosley, 1993).

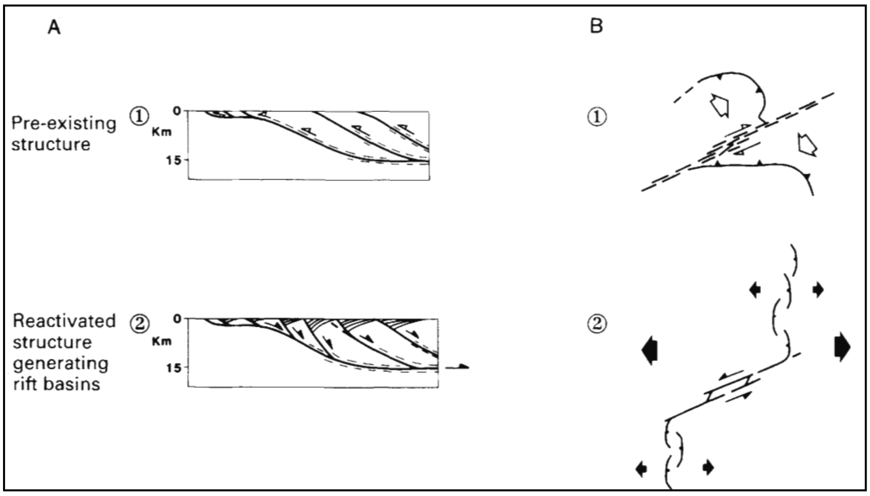


Figure 3.18. Reactivation of low angle structures (Daly et al., 1989). The low angle thrust-sense shear zone is reactivated in extension as a detachment fault.

Whilst pre-existing structures are clearly an important influence on rifting on a variety of scales, they are not the only feature of basement rocks which can affect the development of later brittle structures. The composition and deformational history of basement rocks can have an important role in the origin and evolution of brittle faults (Holdsworth et al., 2001) . Relative differences in mechanical strength between adjacent metamorphic units, for example may be important at both crustal and local scales (Smith and Mosley, 1993).

The processes and chemical changes which take place during metamorphism can have a number of effects on the mechanical strength of the rock. Grain size reduction, the formation of porphyroblasts, veins formed by pressure solution, and the formation of preferred crystallographic orientations can all have marked effects, both strengthening and weakening, on localised structures such as shear zones, and on the bulk rheology of the region being deformed (Passchier and Trouw, 2005). On uplift and exhumation, further retrograde metamorphism can have an additional effect on the composition and strength of basement rocks (Passchier and Trouw, 2005). Many minerals formed during both prograde and retrograde metamorphism to amphibolite facies conditions contain water (amphibole and biotite, for example). The presence of water has a significant effect on the way rocks deform, both by weakening the rocks, and also by affecting the mineral assemblages which form under different phase conditions (Passchier and Trouw, 2005). In metamorphic rocks, process such as hydrolytic weakening introduces water into the molecular structure of silicates. This process has a weakening effect on the silicate minerals themselves, making them more likely to deform under lower strains. Other processes, such as grain size reduction, and the formation of new mineral assemblages can also have an effect on the strength of metamorphic rocks, particularly the development of phyllosilicate minerals such as micas and chlorite. These minerals are significantly weak in certain orientations, and when they define planar basement fabrics, will be easy to reactivate as brittle faults (Beacom et al., 2001; Wintsch et al., 1995).

Relative changes in heat flow within the crust can also contribute to crustal weakening. The brittle – ductile transition, for example, has been hypothesised as a region which could be crucial for the development of large, low angle detachment faults which are thought to form under developing rifts (Hellinger and Sclater, 1983). The brittle ductile transition, however, is not entirely controlled by temperature, and can be a function of rheology, lithology, pressure and strain rate (Lowrie, 2007). More generally, increased heat flow is also thought to play a role in influencing the location of rifts and margins, by reducing the bulk strength of the lithosphere (Kusznir and Park, 1987).

3.2.3.3 Local scale influences

While the most obvious influence on a small scale may be the direct reactivation of basement fabrics and structures (eg. Figure 3.14), it is not the only smaller scale feature that may affect the development of structures in the upper crust. Weaker rocks are easier to fault, and therefore faults and fractures may localise in these regions whilst displaying different dips and strikes to basement structures – therefore not fulfilling the criteria for reactivation. The effect of weaker basement rocks can clearly be seen in other rifts, such as the east-African rift, where rifting has taken place along pre-existing orogenic belts, and cratonic areas remain relatively undeformed (Smith and Mosley, 1993).

On a large scale, orogenic belts may appear to have relatively planar structures. At smaller scales, the dip, strike and structural style of basement fabrics and structures can be more complex. In addition to shear zones and basement foliation, features such as axial planar cleavage, or fold limbs may also present weaknesses that may reactivate or influence the development of later structures (e.g. Osmundsen et al, 2010).

3.3 Structural and stratigraphic development of continental margins

The structural development of continental margin basins is best understood in a framework of large-scale continental margin evolution where discrete continental rifts are a precursor to break-up and oceanic crust development.

3.3.1 Models of large scale margin development

Initially, continental rifts were divided into two end-member groups - passive and active rifts (Sengör and Burke, 1978). In general, active rifts were thought to form as a result of mantle upwelling related to plumes doming and heating of the lithosphere, and therefore were more likely to result in volcanism during the rifting process. Passive rifts were thought to be formed as a result of far field stresses. Most continental rifts do not fit into either category (Ziegler and Cloetingh, 2004).

Another subdivision, which reflects the processes which occur during the formation of the margin, rather than hypothesis on its origin, is between volcanic and non-volcanic margins (Eldholm et al., 1989). Volcanic margins are typically associated with continental flood basalts or mantle plume activity. Offshore, the stratigraphy of volcanic margins is dominated by extrusive igneous rocks, forming ‘seaward dipping reflectors’. Extension is thought to be accommodated at these margins by both faulting, and the addition of material to the extending crust, in the form of igneous intrusions such as dykes (Fig. 3.17). Non-volcanic margins are not thought to have developed in the same way, and are commonly not associated with large scale magmatic activity. These non-volcanic margins are often associated with hyper-extended crust. A type example of this margin type is the Iberia-Newfoundland conjugate margin pair, which shows features related to low angle normal faulting and mantle exhumation (Lavier and Manatschal, 2006). Volcanic and non-volcanic margins are often termed ‘magma rich’ and ‘magma poor’ margins, respectively.

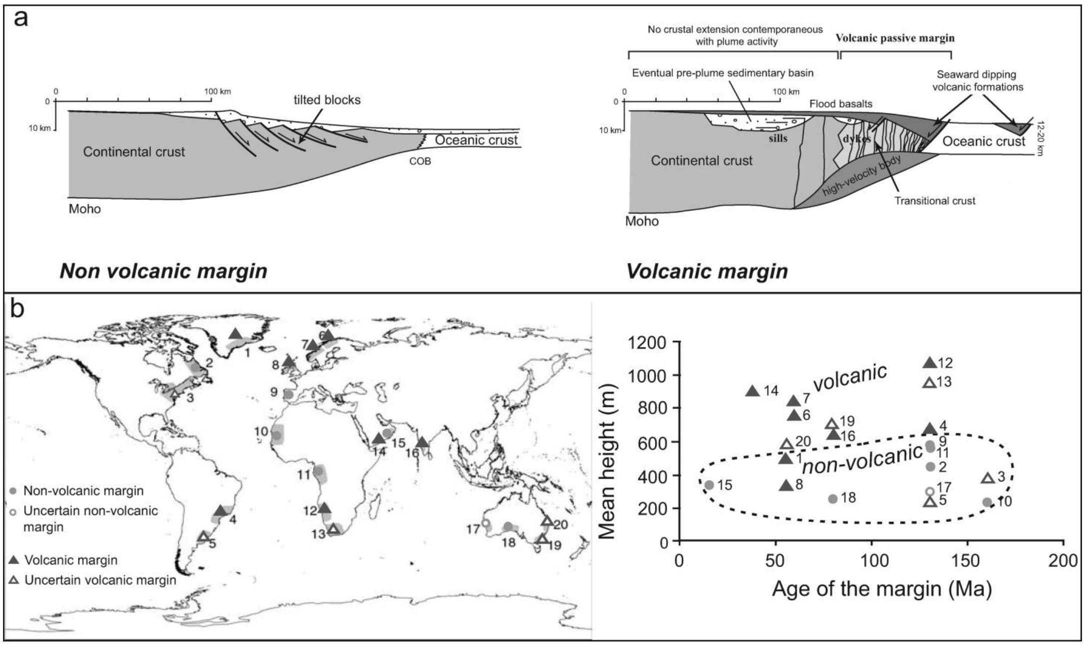


Figure 3.19 – a) generalised cross sections through, and b) distribution of non-volcanic and volcanic margins in space and time (Leroy et al., 2008). There is still significant controversy over both the location and geometry of volcanic and non-volcanic margins.

As continental margins extend, a variety of processes operate, both to accommodate extension, and as a consequence of it. These processes operate on a variety of scales, from cataclasis on individual faults to large scale thinning of the lithosphere.

The response of the crust and mantle lithosphere to stretching is crucial for the evolution of rifted margins, and it can affect many processes during rifting; such as the development of rift-related faults, the location of magmatism, the position of breakup, and the nature of uplift or subsidence during rifting (Ziegler and Cloetingh, 2004).

In terms of lithosphere scale structural development, two other end-member models for rifted margins have been proposed – pure shear and simple shear. Pure shear rifts result from homogenous stretching and necking of the lithosphere (McKenzie, 1978; White and McKenzie, 1988). Simple shear margins deform by non-uniform thinning of the crust, with deformation occurring on a crustal scale inclined plane or shear zone (Wernicke, 1985). Stretching under pure shear predicts uniform distribution and co-location of faulting and magmatism in the upper and lower crust. If a margin has deformed by simple shear, the location of faulting in the upper crust will be offset from the region in which the crust is thinnest, and therefore any rift-related magmatism may occur in a different location from the main rift, and possibly at a different time (Ziegler and Cloetingh, 2004). Rifts which form under simple shear conditions would be highly asymmetric (Fig. 3.18). Again, both of these models are end-members, and as such many margins appear to show features of both pure-and simple shear. Relatively few margins show good evidence for shallow dipping, crustal scale shear zones, which would be predicted by the simple shear hypothesis. Similarly, strong asymmetry of many continental margins, such as those in the south Atlantic, do not fit with the predictions of the pure-shear hypothesis. To address the inconsistencies with each model, combined pure and simple shear models have also been proposed (Kusznir et al., 1991).

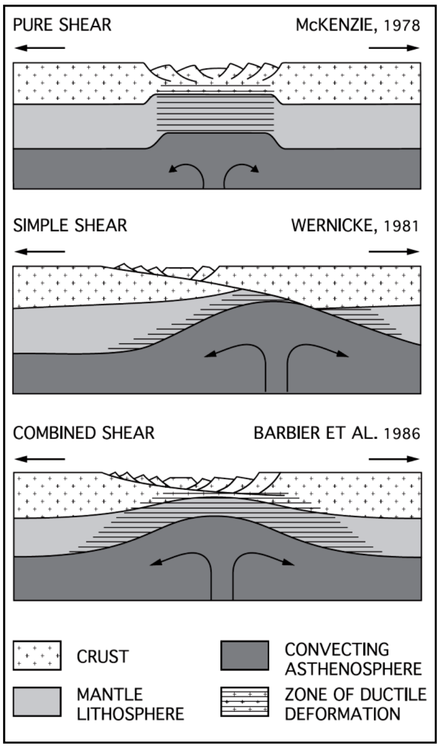


Figure 3.20– Pure shear, simple shear and combined shear models for rifting continental crust (Ziegler and Cloetingh, 2004).

3.3.1.1 Lithospheric response to extension

Since it is a fundamental control on the way basins subside, the distribution of extension throughout the lithosphere in margins which have undergone pure shear (or a combination of pure and simple shear) can have a strong impact on the structural, magmatic and stratigraphic development of rifts. Two main models were proposed in order to explain the distribution of thinning and stretching throughout the lithosphere – ‘Depth dependent stretching’ (Royden and Keen, 1980) and ‘uniform stretching’ (McKenzie, 1978). Uniform stretching predicts that as the lithosphere is extended, thinning and stretching will be evenly distributed throughout the crust and upper mantle. By contrast, depth dependent stretching predicts that more of the extension is accommodated in the lower crust and upper mantle, due to rheological differences.

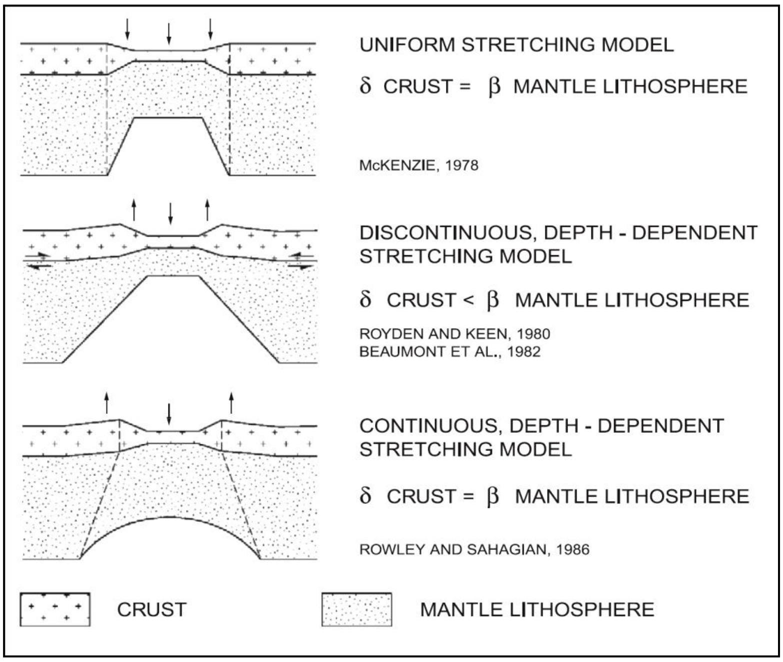


Figure 3.21 – Models for large scale stretching of the lithosphere (Ziegler and Cloetingh, 2004).

Different models of basin extension result in different predictions of subsidence and fill histories for the basin. In depth-dependent stretching models, a rapid initial fill, in which the entire lithosphere is extended, is followed by a decrease in rates of sedimentation as the basin subsides isostatically, due to differences in the density and thickness of crust and mantle. The characteristic geometry of basins which have formed by depth dependent stretching is known as the 'steers head' (White and McKenzie, 1988). In contrast, to the subsiding region at the centre of the rift, rift flanks would form highs due to the thinning of the dense mantle lithosphere and the associated increase in geothermal gradient. Basins which have deformed by uniform stretching would experience the rapid initial subsidence and fill, but would experience less late subsidence. The uniform stretching model would also result in a smaller isostatic response after rifting (i.e. less thermal subsidence and rift-flank uplift), since there is less extension in the lower crust and mantle than is predicted by the depth dependent stretching model (Davis and Kusznir, 2004). In light of these differences, and many different geological and geophysical data which support the depth dependent stretching model over the uniform stretching model, the depth dependent stretching model is now more widely used.

As a result of depth dependent stretching, hot asthenospheric mantle may replace cool lithospheric mantle under the thick rift flanks, in addition to the centre of the rift. This can lead to rift flank uplift, and thermal sag in the centre of the basin, due to thinned lithosphere. It also leads to increased chance of melting, as hot asthenosphere is taken to lower pressures. Other factors, such as relative enrichment in volatiles, and the composition of the mantle lithosphere can also affect the way mantle can melt in rift zones, because different mantle minerals melt under different P/T conditions (Wilson, 2007).

3.3.1.2 Hyperextension

Hyperextended passive margins are defined as those which have large degrees of extension and thinning, and have <10km thick crust over 100's of kilometres width (Unternehr et al., 2010; Whitmarsh et al., 2001). Hyperextended margins are typically magma-poor (whilst magma-rich margins can be wide, they are not regarded as hyperextended because much of the extension is accommodated by intrusion of magma into the crust, rather than by extensional faulting (Geoffroy, 2005).

The Santos basin is often invoked as an example of a hyperextended margin (Reston, 2010). The way in which extension is accommodated on hyperextended margins is debated, as typically the offset measured on visible faults does not account for the total thinning and extension seen on the margin. Two major theories to explain this discrepancy are currently under debate. One theory involves significant amounts of extension being accommodated on low angle normal faults (Lavier and Manatschal, 2006), whilst an alternative model (termed the 'fault rotation model' in this thesis) depends on the progressive rotation of faults to an angle at which they can no longer slip (Reston, 2009), at which point they are cross cut by later faults. After several generations of this faulting, it is increasingly difficult to identify individual faults (faults which have rotated to be sub-horizontal may be confused with bedding), leading to an apparent extension discrepancy.

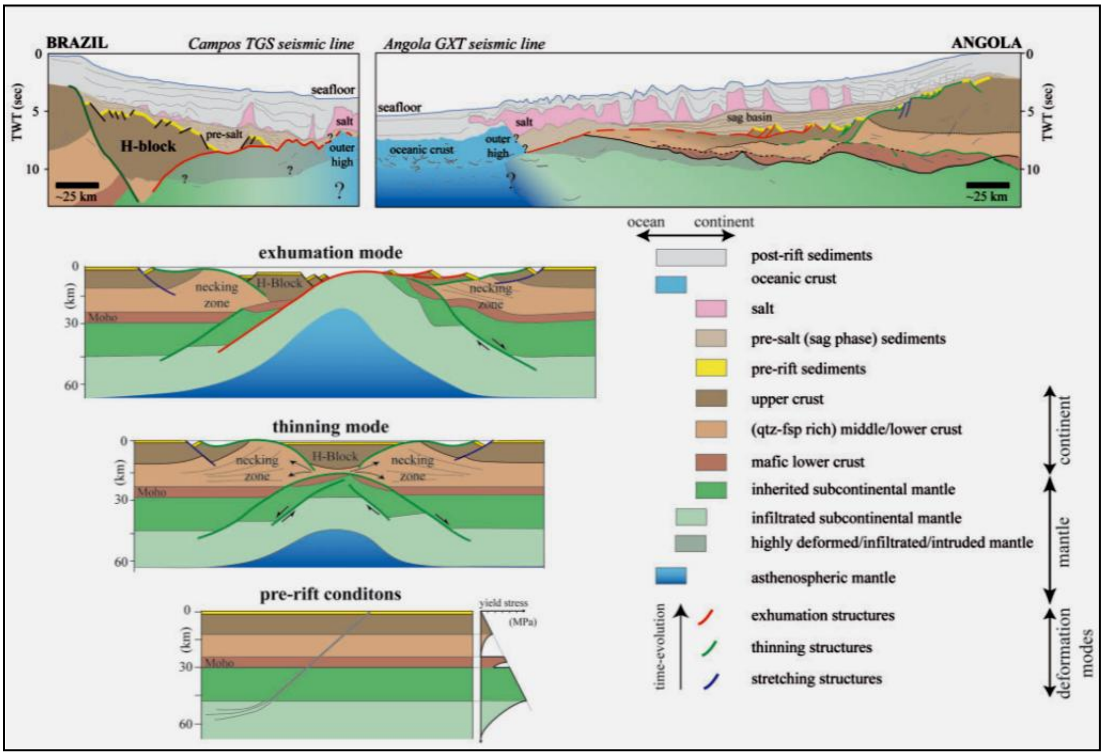


Figure 3.22 – Hyperextended margins in the south Atlantic (Unternehr et al., 2010). This model is based on the 'low angle normal fault model', and predicts possible mantle exhumation due to hyperextension, and faults that are continually active at low angles throughout rifting.

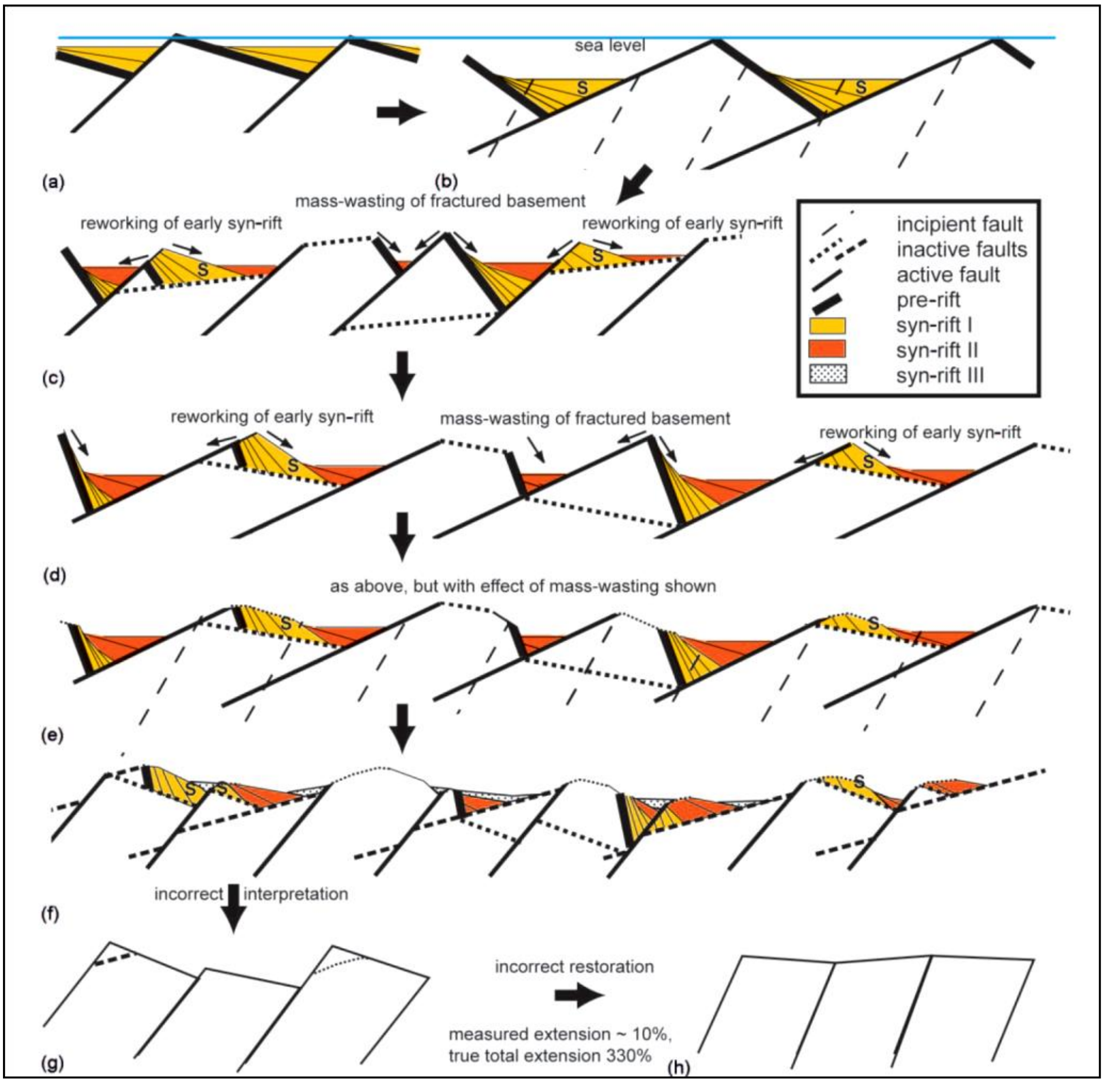


Figure 3.23. The 'fault rotation model' (Reston, 2009). Whilst not incompatible with other models for hyperextension, this model predicts multiple phases of rifting on structures which form due to pre-existing structures rotating to angles at which they are unable to slip. Careful attention needs to be paid to restoring such models, as their complex geometries are often difficult to interpret.

Both models are largely based on offshore seismic data and theoretical modelling, however they each have support from field and other geological data. The 'low angle normal fault' model is largely based on outcrop data from the Alps, together with samples drilled from the ocean floor on the Iberia-Newfoundland margin, whilst faults rotating and being cross-cut is thought to have been observed in the Basin and Range province, western USA (Proffett, 1977). Few other examples of this type of faulting are reported in the literature.

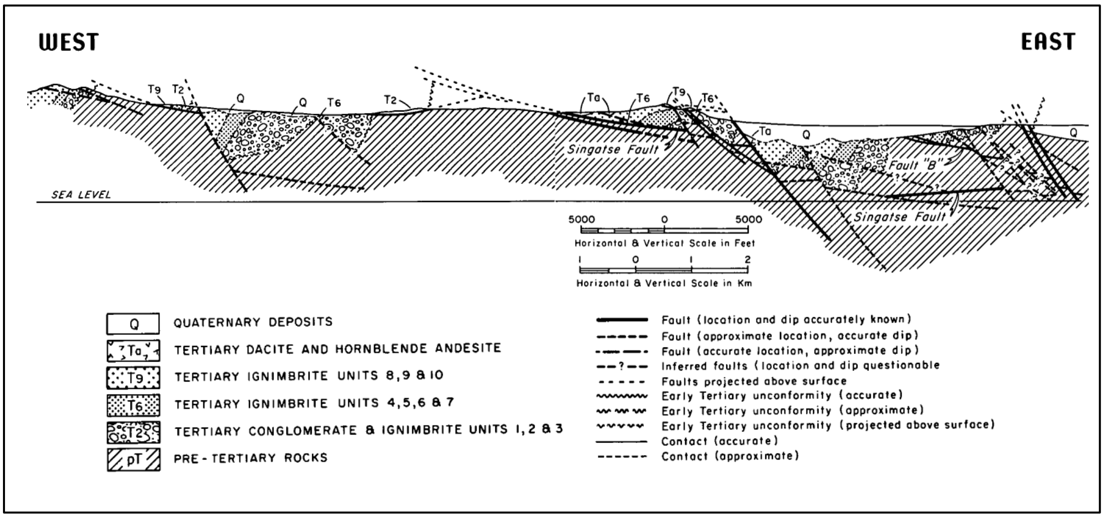


Figure 3.24 – A cross section through the Yerington district, Nevada (Proffett, 1977). The section shows how older faults have been rotated and are crosscut by younger, higher angle faults. This section provides field based support for the 'fault rotation model'.

Each model is very successful at explaining potential reasons for the apparent extension discrepancy in the region for which the model was developed. The low angle normal fault model explains the extension across the Iberia-Newfoundland margin), whereas the 'fault rotation' model explains extension in the Basin and Range (USA), and the Porcupine basin. A criticism of each model could be that they are based on limited natural examples, and applied to margins around the world. Another is that they are based on relatively ambiguous data – low angle reflectors in seismic that may be difficult to interpret as faults if they show little or no apparent offset. For these reasons, it is difficult to interpret offshore seismic data in the context of either model with great certainty.

Compressional structures have been observed on some hyperextended margins, formed both before and after breakup. Lundin and Dore (2011) suggest that the formation of hyperextended margins has a long term weakening effect on the lithosphere, due to the serpentinisation of the upper mantle as it is exhumed. This effect leads to further deformation (both compressional and extensional) occurring more easily (Lundin and Doré, 2011).

3.3.2 Fault growth and linkage, and its affect on rift geometry

A problem with all of the models discussed above, and with larger lithospheric scale models (e.g. Huismans, 2011, and many other works dealing with depth dependant stretching and bulk lithosphere behaviour), is that they are essentially 2 dimensional representations of a 3 dimensional system. Changes in passive margin geometry and kinematics along strike are common, and therefore map view geometries need to be considered, in addition to 2D cross sections, when trying to understand their evolution.

As faults develop from incipient microcracks into larger structures, the way in which stress is transferred between structures can have a strong impact on their development and geometry, and on the fill history of the rift. As faults propagate, stress is transferred along strike, leading to smaller faults linking to form larger structures (Cowie et al., 2000). Faults that are not found along strike from these larger structures are more likely to become inactive. Small, isolated half grabens may fill with sediments whilst larger faults continue to develop and link, controlling the larger scale rift architecture. These faults can control the locations of structural highs and depocentres, and the understanding of the processes relating to their development is crucial when understanding both large scale structural evolution and small scale depositional processes during rifting (Fig. 3.24)

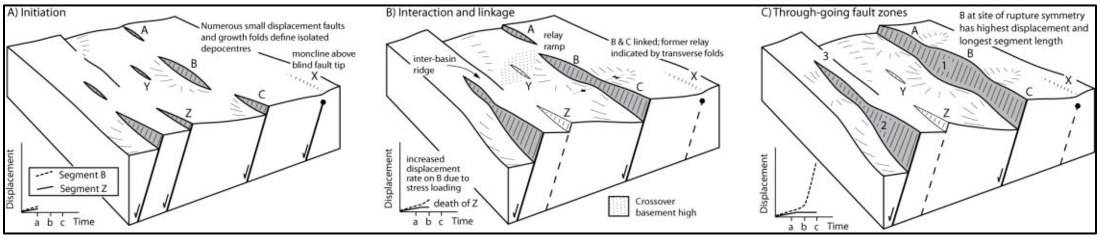


Figure 3.25 - Fault linkage and propagation during early rifting (Gawthorpe and Leeder, 2000).

When margins develop obliquely, faults which develop parallel to the trend of the rift may be unable to accommodate all of the deformation by oblique slip alone. Transfer zones are thought to form in order to accommodate either complex local strains in regions between offset or overlapping normal faults, or to accommodate oblique components of regional stress that cannot be accommodated on antithetic and synthetic rift related faults (Faulds and Varga, 1998). Transfer zones can play a role in compartmentalising the basin, and can separate zones of different deformation (such as in a partitioned system, as described earlier). They may be ‘hard linked’ discrete structures (Fig. 3.24), or ‘soft linked’ zones of deformation, which are larger regions across which deformation is accommodated (Faulds and Varga, 1998). They typically form significantly oblique or even orthogonal to the trend of major structures in the rift (Gibbs, 1984). Whilst they are interpreted in many basins worldwide, their presence is controversial, and in some regions, transfer zones interpreted from regional gravity and magnetic surveys have been interpreted significantly differently with the use of high resolution seismic data (Moy and Imber, 2009).

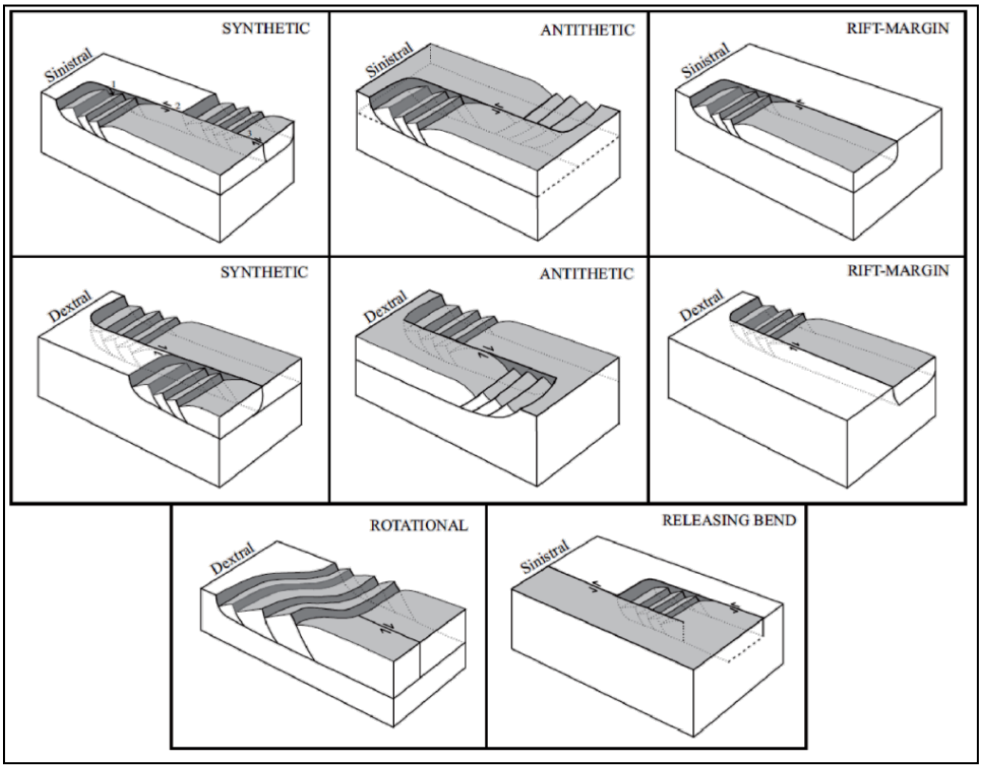


Figure 3.26 - Geometries of transfer zones (Faulds and Varga, 1998). Transfer zones can display a wide variety of geometries, either seperating zones of different fault geometries, or offsetting and affecting the positions of faults with similar geometries.

3.3.3 Regional uplifts

Large scale, elongate regions of elevated topography are commonly observed on passive margins around the world. Their causes are not well understood, and various models have been proposed, including rift flank uplift, the role of mantle plumes, dynamic topography driven by mantle convection, and isostatic processes (Japsen and Chalmers, 2000). If these processes occur during rifting, they can have a strong impact on the structural development of the early rift, whereas it they are caused by processes which occur after breakup, they will have an effect on the post-rift fill history, and may form new, post-rift structures, and reactivate syn-rift faults and fractures (Japsen et al., 2011; Osmundsen and Redfield, 2011; Osmundsen et al., 2010). Broad uplifted regions can be observed on the Norwegian, east Greenland, Brazilian and Red Sea margins, among others around the world.

The timings of uplift in these regions are frequently derived from apatite fission track, a method to understand heating and cooling in rocks. Heating is assumed to reflect burial, whereas cooling reflects exhumation (although other heating and cooling processes are recognised) (Bray et al., 1992). This exhumation is often regarded as a proxy for uplift. By dating apatite crystals it can therefore be possible to identify times of exhumation and burial. Another assumption made by these studies is that the current morphology of the uplifted region reflects the topography before uplift and exhumation. These regions are thought to have once been low level erosional surfaces, or peneplains. After uplift, these can be mapped and their relative heights used to determine amounts of uplift (Bonow et al., 2006). Apatites from these peneplanation surfaces can then be dated and timings, and amounts of uplift from sea level established. Offsets in these peneplains can be used to infer the locations of faults formed during the exhumation events (Bonow et al., 2006).

These studies have shown that exhumation events in these regions are rarely single events, and many appear to show pulsed uplift and burial events, suggesting that their origin is perhaps not as simple as an isostatic response to rifting. Furthermore, dating of these uplift events shows that they commonly occur around 30Ma after rifting has initiated, calling into question their interpretation as rift flank uplifts. Osmundsen and Redfield (2011) link the final geometry of uplifted regions to the crustal thinning process, and the location of the ‘taper break’, which is defined as the location at which crustal thickness has decreased to 10km as a result of extension (Osmundsen and Redfield, 2011). As the region is uplifted, the framework of structures formed during rifting have a strong effect on the geometry of the uplifted region. Whilst this relationship has been observed on a number of margins, as yet there is no explanation for why this geometry forms, although rift related structure clearly plays a role. Alternative explanations for these uplifts as mantle plumes during rifting have been proposed, particularly for the south Atlantic, but dating of uplift events suggests that this may not be the case, as many exhumation events postdate the timing of the mantle plume (Gallagher et al., 1994; Hackspacher et al., 2004).

The great escarpment in southern Africa is thought to have been uplifted by the ‘southern African superswell’ in the last 10Ma (Lithgow-Bertelloni and Silver, 1998). Whilst this appears to be caused by dynamic topography, as opposed to the rifting process, it may overprint an earlier uplift event. The margins of the Red Sea currently show large uplifted regions, and have formed much sooner after rifting than the 30Ma that has been suggested for other rifts. It may be the case that, as for models for hyperextended margins, different uplift models apply to different margins, and that apparently similar structures could have different origins.

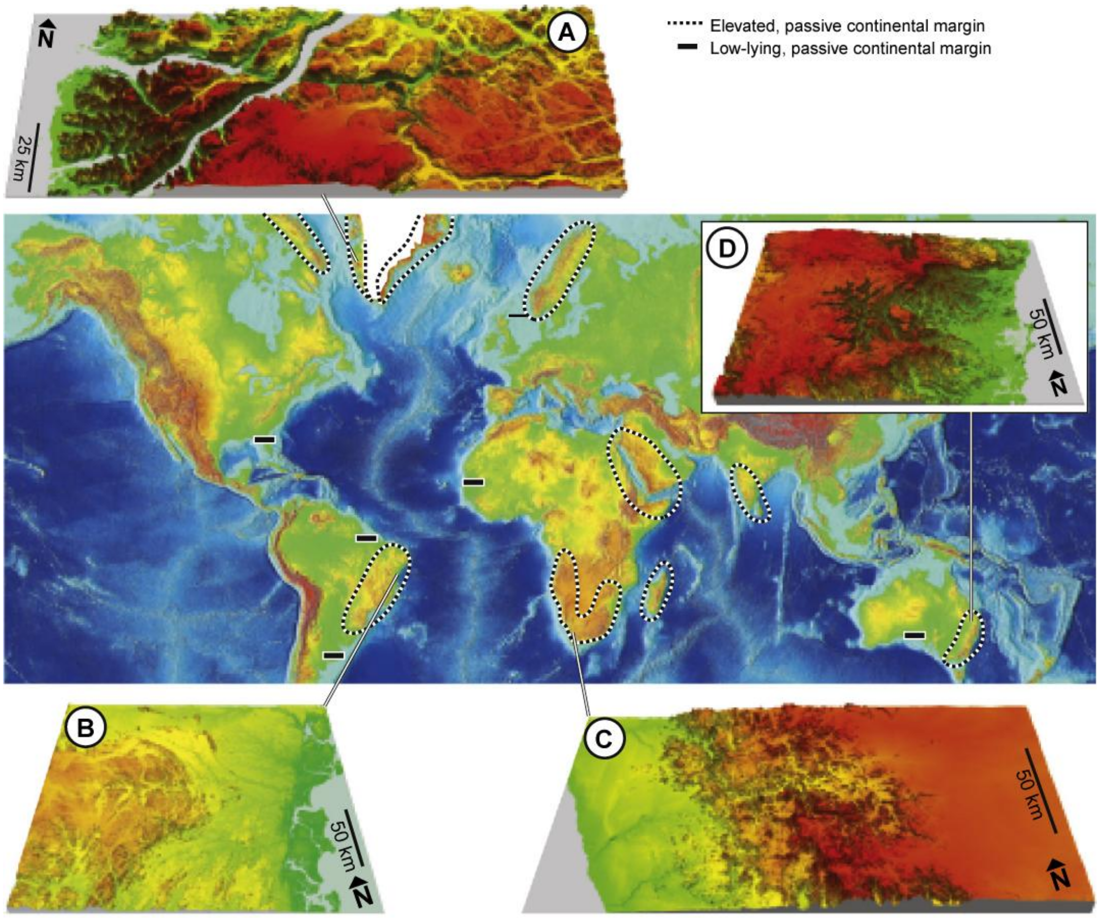


Figure 3.27. Location of uplifted rift margins worldwide (Japsen et al., 2011) . Uplifts on margins commonly show asymmetric profiles, with a steep slope on the oceanward side, and shallow slopes dipping towards the hinterland.

3.3.4 Magmatism at continental margins

Passive margins commonly display features relating to magmatism and volcanism. An understanding of the magmatic evolution of margins is important because heat flow, igneous intrusion, and volcanism can all affect the stratigraphic and structural development of the margin. These affects will be discussed within this section.

3.3.4.1 What causes magmatism during extension?

There are a variety of possible causes for magmatism and volcanism at continental margins, and most are related to the crustal thinning process, the action of mantle plumes, or both. Melting can occur as a result in changing the temperature, the pressure or the relative enrichment in volatiles, in lithospheric or asthenospheric material beneath a rift zone (Wilson, 2007).

Rift processes are modified by magmatism in a variety of ways (White, 1992). Many rifts, such as those in the south Atlantic margins become ‘volcanic margins’ with widespread volcanism including the presence of seaward dipping reflectors formed by prograding lava flows in the stratigraphy of the basins. Large amounts of igneous intrusion may take place into the crust in the form of dykes and sills (Geoffroy, 2005). The lower crust may also be underplated by igneous rocks, affecting its density and therefore its response to isostatic processes, and the amount of uplift that may occur.

In the south Atlantic margins, particularly those south of the Florianopolis fracture zone, such as the Pelotas basin, volcanic features, such as seaward dipping reflectors are very evident (Abreu, 1998). North of this, the margins are assumed to be magma poor, or non-volcanic (Zalán et al., 2011). These margins, however, display numerous features consistent with rift-related volcanism, such as dykes and extensive lava flows, both in the onshore Paraná basin, and in the offshore basins, as discussed in the regional geology section (Chapter 2).

The intrusion of dykes forms a prominent part of the evolution of many margins, and in some cases, dykes are thought to accommodate a significant amount of extension. In some cases, up to 80% of local extension is thought to have been accommodated by dyke injection (Geoffroy, 2005). The kinematics of dyke intrusion may have a significant effect on the way continental margins develop, and an understanding of the geometries that dykes form as they intrude, both on a local scale and a regional scale, is crucial in order to understand the margin as a whole.

3.3.4.2 Dyke Swarms

Dyke swarms form where large numbers of dykes intrude a region at a similar time, usually in response to a single magmatic event. Orientations of dykes within a swarm may be parallel, form conjugate sets, or be radial. Dyke swarms occur in a variety of tectonic settings throughout geologic history, and can have a variety of origins (Ernst et al, 2001). In this section, I will focus on dyke swarms that form as a result of extension, as opposed to those that form in non-extensional settings.

Dykes are found at a variety of margins, and dyke swarms have been recognised in both the north and south Atlantic (Turner et al., 1994; Wager and Deer, 1938). The origin of south Atlantic dyke swarms is debated, and the main causes are thought to either relate to mantle plumes or the crustal thinning process. The radiating nature of many dyke swarms worldwide is thought to reflect the role of mantle plumes in their origin (Ernst et al., 1995), due to the stresses associated with regional doming (Burke and Dewey, 1973). In south-eastern Brazil, three dyke swarms have been interpreted as a triple junction, suggesting their origin relates to crustal extension, rather than plume activity (Coutinho, 2008). Dykes actively intruding as part of a ‘triple junction’ are found in the Afar region of eastern Africa (Wright et al., 2006).

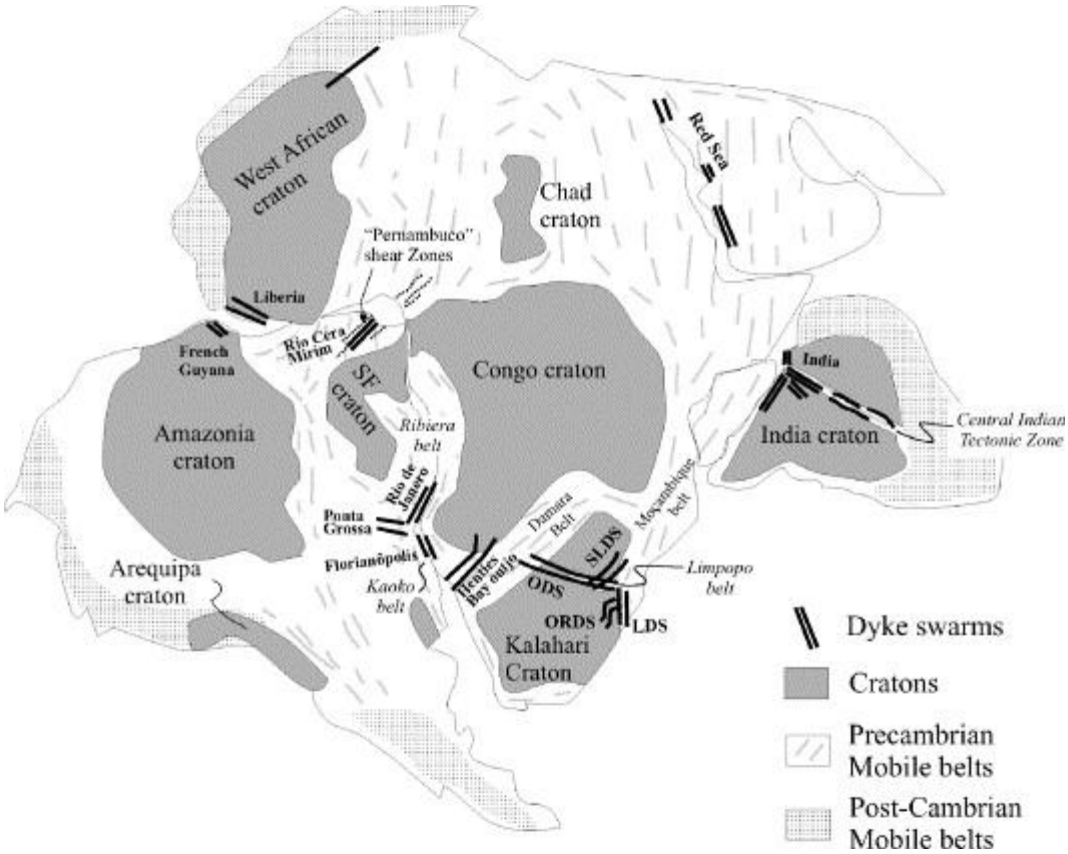


Figure 3.28 - The location of Phanerozoic dyke swarms in Gondwana (Jourdan et al., 2006). Many of these swarms formed during the early stages of Gondwana breakup, and many lie parallel to cratonic boundaries and have intruded mobile belts.

The geodynamic and kinematic significance of dyke swarms can be understood by considering the mechanisms by which they intrude, in terms of both igneous and structural processes. The major processes involved in dyke intrusion is hydraulic fracturing (Lister and Kerr, 1991). When a dyke intrudes by hydraulic fracturing, the force on the country rock, exerted by overpressured fluids and gases in the tip of the propagating dyke fractures the rock ahead of the intrusion, creating a space into which the magma intrudes. Hydraulic fracturing occurs in settings where differential stresses are high (Cosgrove, 1995). If differential stresses are low, dykes can also respond to regional extension, infilling pre-existing fractures, or fractures which form in response to regional stresses. Joints commonly form parallel to the dyke as it intrudes (Delaney et al., 1986).

3.3.4.3 Dyke Intrusion

Since a dyke intruding by hydraulic fracture needs to break the rock in order to intrude, the force of the overpressured fluid needs to overcome the strength of the rock being intruded. Clearly, when the rock is weaker, or pre-existing weaknesses are present within the rock, a dyke intruding by hydraulic fracturing will tend to exploit these weaknesses. Assuming little or no regional stress present during the fracturing of a rock, it will be much more difficult for a dyke to fracture a competent rock with little heterogeneity, than it would be to intrude a rock containing pre-existing heterogeneities (depending on the orientation of those heterogeneities relative to the regional stress field). If a heterogeneity is present, the force of the dyke intruding will need to overcome the normal stress acting on the fracture in order to cause it to open (Jolly and Sanderson, 1997). If dykes have intruded by infilling pre-existing fractures, their geometry will likely be dictated by the orientations of the fractures (Baer et al., 1994). If dykes intrude into a region which is undergoing extension, they will open perpendicular to the minimum principal compressive stress, thus explaining why many dyke swarms consist of parallel dykes. Which of these mechanisms is dominant is likely to be dependent on the orientation of the fractures relative to regional stresses (Pollard, 1987). Some evidence also exists for the oblique opening of dykes, which may suggest dykes are intruding into obliquely opening fractures, although this may reflect deformation across the dyke during intrusion (i.e. while it is still molten) (Glazner et al., 1999).

As dykes intrude, both fluid dynamics and local and regional stresses can affect the way they fracture the host rock, and the structures that form as a result. An understanding of these processes is fundamental when interpreting outcrop scale structures. Jogs in dyke margins, pinching out of ‘offshoots’, or ‘apophyses’ (smaller dykes, linked to a larger structure, intruding the country rock near the dyke), joint patterns within the dyke and rifted pieces (or xenoliths) of host rock within the dyke can all be used to interpret both dyke propagation direction and whether it has intruded by fracturing the country rock, or by infilling pre-existing fractures (Hoek, 1991).

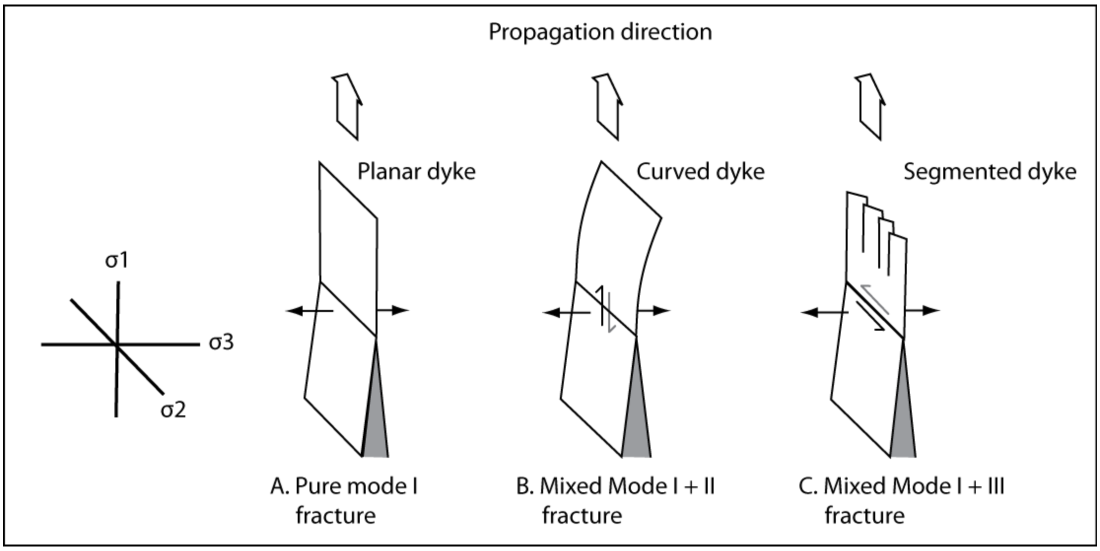


Figure 3.29 – modes of dyke propagation, modified from Pollard (1987). Whilst dykes primarily intrude perpendicular to the regional minimum compressive stress, local stresses can also affect the way they form, with mode II and III type fractures forming as shear is applied to the dyke margins during intrusion.

Dykes intrude as a sheet like body, in response to regional stresses and magmatic overpressure. In general, they will travel both away from their source (e.g. a zone of melt or magma chamber within the lithosphere), either laterally or vertically. Since dykes are fluid as they intrude, the front of the dyke as it intrudes is rarely a flat edge, and commonly consists of 'fingers', which intrude separately, linking at depth to form a continuous sheet (Pollard et al., 1975). As these 'fingers' intrude, they form en-echelon geometries, dependent on intrusion direction and regional stresses. The country rock between and around fingering dyke segments forms characteristic geometries, such as bridges, jogs and braids in the dyke margin. These geometries can be restored to give a sense of how the dyke has intruded its propagation direction and any evidence of oblique opening (Glazner et al., 1999). The key piece of evidence, however, for oblique opening is the presence of clearly offset structures, such as bedding or veins across the dyke.

3.4 Summary

The manner in which continental margins develop is potentially influenced by a large variety of factors. The structural development of a margin is clearly related to any obliquity between the orientation of rift related faults and the regional extension vector. This oblique rifting can result in the development of complex transtensional structures, and partitioning of deformation into wrench- and extension-dominated domains. The presence of igneous intrusions can also fundamentally affect the way a region deforms by transtension. The role of basement structures may also be important, with pre-existing weak structures likely to focus brittle deformation.

Large scale processes, in conjunction with those that operate at smaller scales, such as fault linkage and propagation can fundamentally affect the structural and stratigraphic development of offshore basins. The occurrence of magmatism during rifting, in addition to affecting the large scale evolution of the margin, can also influence fractures and faults forming during dyking events. An understanding of the structural and tectonic processes influencing margin evolution is clearly fundamental, in addition to a good understanding of regional geology.

4 Margin scale tectonic geomorphology

In this chapter, I report and discuss a regional-scale remote sensing study of the onshore regions adjacent to the Santos basin in south-eastern Brazil (Fig. 4.1), and equivalent regions adjacent to the Kwanza and Namibe basins in south-western Africa. The primary dataset for this study are morphotectonic lineaments, picked from digital elevation models using ArcGIS software. A lineament orientation analysis was used to determine regional trends, and also to establish local variations in lineament patterns that might reflect smaller-scale structural variations.

4.1 Lineament analysis

Lineament analysis is the method of extracting linear features from maps, aerial photography, satellite imagery and digital elevation models. It involves the identification and digitisation of linear and curvilinear features on remote sensed data either automatically using computer programmes (Clark and Wilson, 1994) or manually (Gabrielsen et al., 2002).

The main advantages of the method are that it is a relatively quick and easy way to study the geometries of geological structures across a large area. The method is, however, strongly dependent on the interpreter, or computer program, and different picking methods will lead to different results using the same data.

4.1.1 What is a lineament?

A lineament is any linear geomorphological or geographic feature (O'Leary et al., 1976). It may be a ridge, a valley, a river, or an abrupt change in elevation or geomorphology, among other things. Lineaments are assumed to relate to bedrock geology and structure, or landscape features formed by purely geomorphological processes. The lineaments and the features which form them will relate to the geological history and evolution of a region, and can provide information on the geometries of, and relationships between, regional scale faults, basement fabrics, and geomorphological features. In this study, the objective of the lineament analysis is to understand the basement influence on brittle faulting, and thus attempts were made to avoid picking other geomorphological structures.

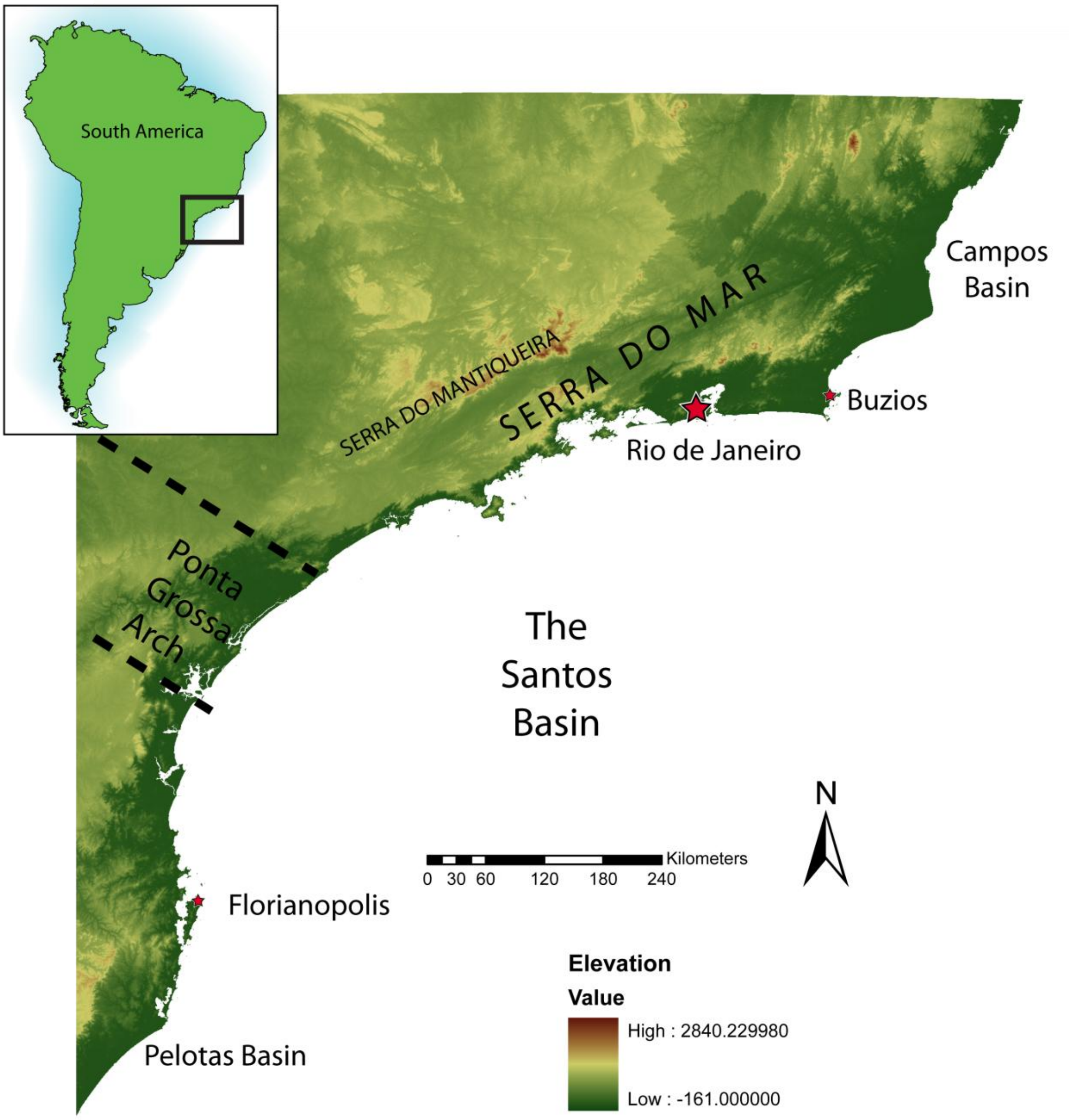


Figure 4.1 - The location of the Brazilian lineament study area. The SRTM topographic data used for the lineament study is used in this image, shaded by elevation. Major geographic features are labelled.

4.1.2 Manual or automatic picking?

Lineaments can either be picked manually, with a human interpreter deciding which lineaments to pick, based on a set of predefined criteria, or automatically, where a computer program is used to pick lineaments based on parameters that it is given.

Automatic lineament studies are much faster than manual studies, but, offer less control on which lineaments are picked, and may be unable, for example, to distinguish between manmade features and natural ones. Equally, they are less able to distinguish between features related to bedrock geology, and those related to superficial sediments (lines of sand dunes, for example, or multiple channels in a river delta). In some cases, geomorphological features can be closely related to, and influenced by bedrock geology, for example, rivers which follow or deviate along faults. In such cases, it is important to be able to distinguish between those features which are purely geomorphological in origin, and those which have been influenced by basement geology.

The key advantage of a manually picked lineament study is that the interpreter is able to filter out certain features (rivers, roads etc.) that are not relevant to the study. However the interpreter selection of lineaments is a source of bias in itself. This has been documented in studies where multiple observers were given the same dataset and achieved very different results (Boucher, 1997; Short, 2009). It is important to define what is meant by a 'lineament' within the scope of the present study. Here, lineaments were defined as long, linear geomorphic feature with apparent tectonic origin, rather than geomorphological features with no tectonic origin. The nature of the study will also determine which data to use, since data type, resolution and scale can all be important. Small scale studies, for example will require detailed, high resolution data, such as aerial photographs and airborne Lidar data. For regional scale studies, such detailed data would be inappropriate, as regional scale features are likely to be visible on lower resolution data which covers a much wider area.

4.1.3 Data Used in this study

Lineaments were picked from SRTM 90m digital elevation models (DEM) (USGS, 2006). The Shuttle Radar Topography mission (SRTM) involved the use of radar based on the space shuttle to collect topographic data from almost the entire globe . Pixels have 90m resolution, and data coverage is constant, other than in the highest latitudes (Farr et al., 2007). Such datasets offer a good balance of resolution and practicality when dealing with large regions. The disadvantage, when compared with true or artificial colour imagery such as Landsat, is that it is difficult to visually identify the geological origin of the features being studied. Previous studies, for example, Gabrielsen et al (2002), have concentrated only on brittle structures and have gone to great lengths to avoid picking foliations in metamorphic rocks. Due to the amount of vegetation in this part of Brazil, this is not possible, and therefore the additional visualisation of bedrock features which Landsat potentially offers are not applicable to the area. SRTM data also compares favourably with Landsat data, or higher resolution DEM data such as ASTER GDEM, due to smaller file sizes. This allows more data to be used and interpreted without the need for powerful computers. Whilst the Landsat data can lead to the identification of smaller features, it would simply not be practical for such a large scale study. A third consideration, which will be discussed in further detail later, is that Landsat and other satellite or aerial photographic data, is inherently biased by the angle of the sun. While features trending at high angles to the insolation angle are clearly highlighted, it can mask features that lie parallel to it. DEM data allows insolation to be artificially set at any angle, allowing this data bias to be avoided.

4.1.4 Data Visualisation

The basic topographic dataset consists of 90m wide pixels, with an elevation value based on their average height above sea level. The simplest way to visualise this data would be to colour each pixel according to its elevation. This method works well for visualising large areas of topography, but can make it difficult to identify more subtle topographic features, especially in areas with large ranges of topography. Such a method can also lead to erroneous interpretations, for example, plotting linear features on an evenly dipping surface, where the colours in the scale change. One improvement is to use a hillshade, where an artificial illumination (or insolation) angle is set, and the topography is shaded relative to this imaginary light source, using the 3D analyst toolbar in ArcGIS 9.2 (ESRI, 2006). If the data is illuminated from the northeast, for example, northeast facing slopes will be bright, whilst southwest facing slopes are in shadow. This can be overlain on the coloured data to give a more realistic view of the Earth's surface or can be used alone as a greyscale image. It is important to note that multiple hillshade directions need to be used as linear features trending parallel to one illumination direction will not be illuminated or cast into shadow, and may be invisible (Dehandschutter, 2001)

The data can be processed in a number of other ways. Slope shading, where the data are coloured by the slope angle, highlighting steep slopes and shallow slopes, can highlight linear features. However, this may fail to differentiate ridges and valleys, especially those with equally steep sides; such features typify the majority of lineaments on these scales. Aspect shading, where the pixels are coloured according to the direction they face, can also highlight such features, but does not offer any significant advantages over hillshading, especially when multiple hillshades of different angles are used.

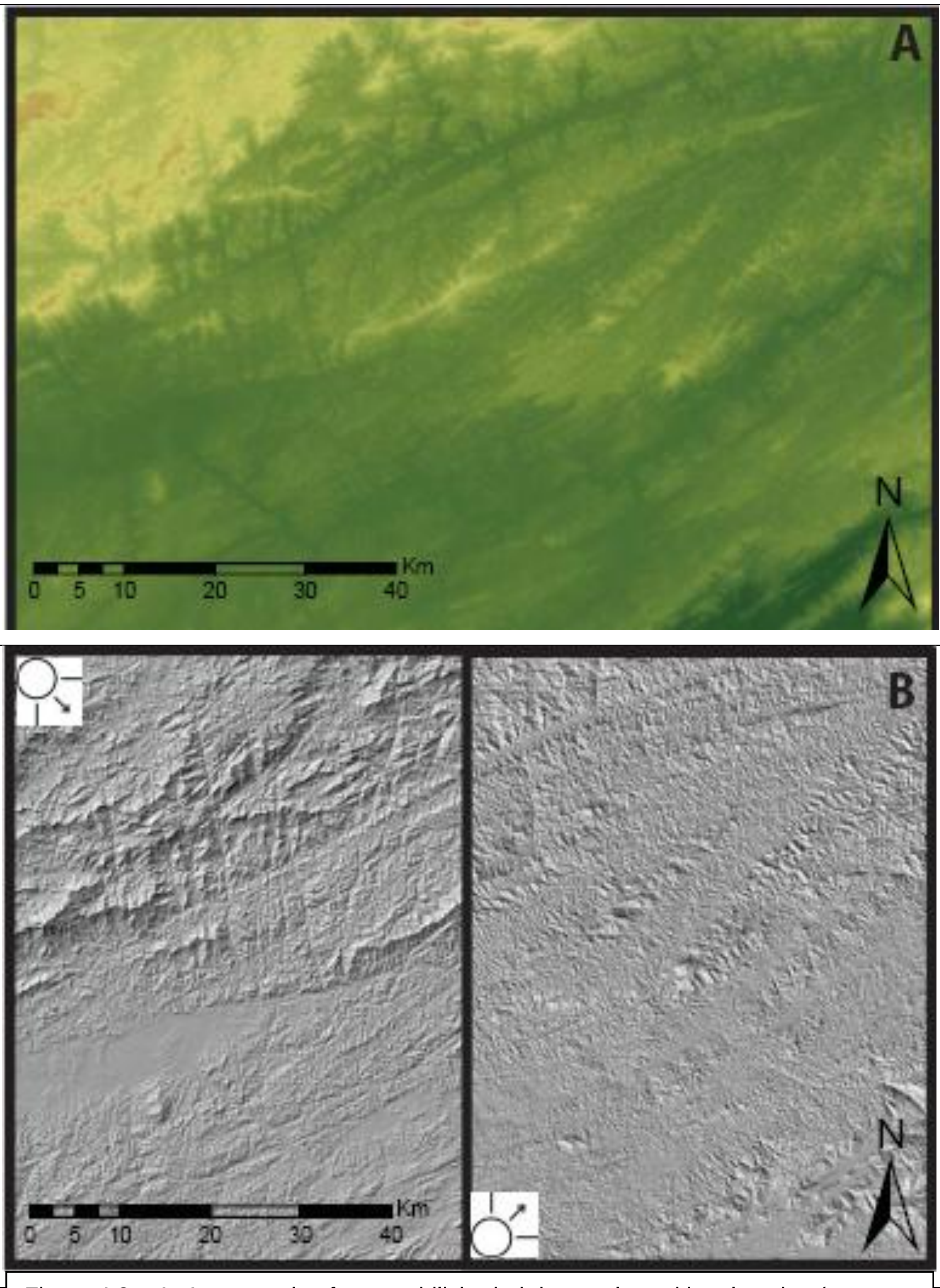


Figure 4.2 – A: An example of raw, unhillshaded data, coloured by elevation (green = low, brown = high). Lineaments may be identified from these data, they are not clear, and attention is drawn to regions where the colour changes. B: The same data having been hillshaded. The right hand image has been illuminated from 225°, whilst the left hand image is illuminated from 325°. The right hand image clearly shows that structures in a NE-SW orientation, parallel to illumination are difficult to see, whereas structures at high angles to this are much clearer.

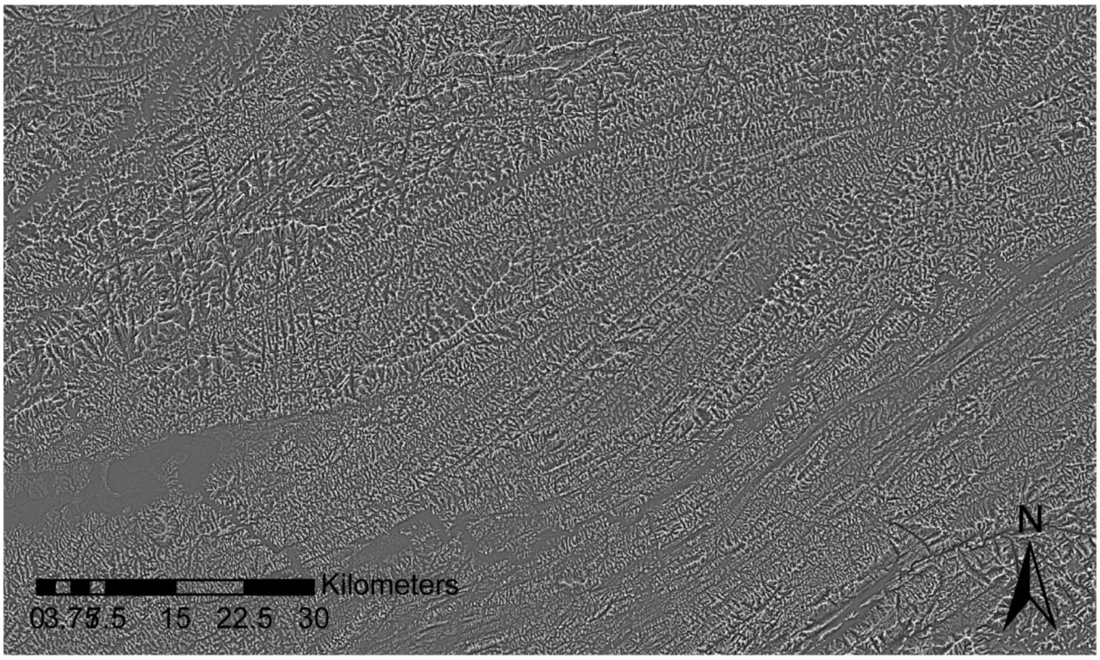


Figure4.3 – The same data shown in figure4.2, with an edge-enhancing filter applied (using the ArcGIS ‘filter’ tool). This method makes lineament picking simple, but data has lost ‘real world’ context. Large, clear lineaments are indistinguishable from small, less significant lineaments based on this data, as are lineaments picked from largely flat areas, when compared with those picked in mountainous regions.

Topographic data can also be filtered, either to enhance edge detection, or to smooth edges. Since this study is based on long linear features, edge detection filtering may be appropriate. The program passes a moving window over the data, which processes the data to ignore large wavelength variations and magnify low wavelength features (Short, 2009). This highlights features such as cliffs, whereas broad elevation changes are ignored. Filtering can extract many linear features, and is the method used by a number of automated lineament picking methods. I did not deem it appropriate for this study since the resulting datasets offer very little in the way of geological or geographical context.

4.1.5 Software

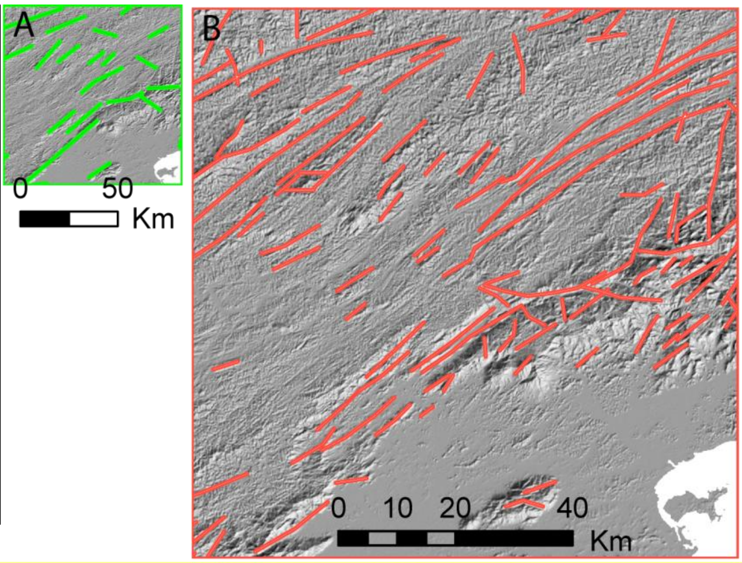
All lineament data was analysed using ArcGIS software. Lineaments were picked as shapefiles, directly from topographic data. Using ArcGIS, multiple datasets can be overlain and compared, and data can easily be collected at a variety of scales. Rose diagrams were created using GMT to analyse the lineament data (Wessel and Smith, 1998), GMT is a command line-based program, which allows for the speedy processing of large lineament datasets, using its 'psrose' function.

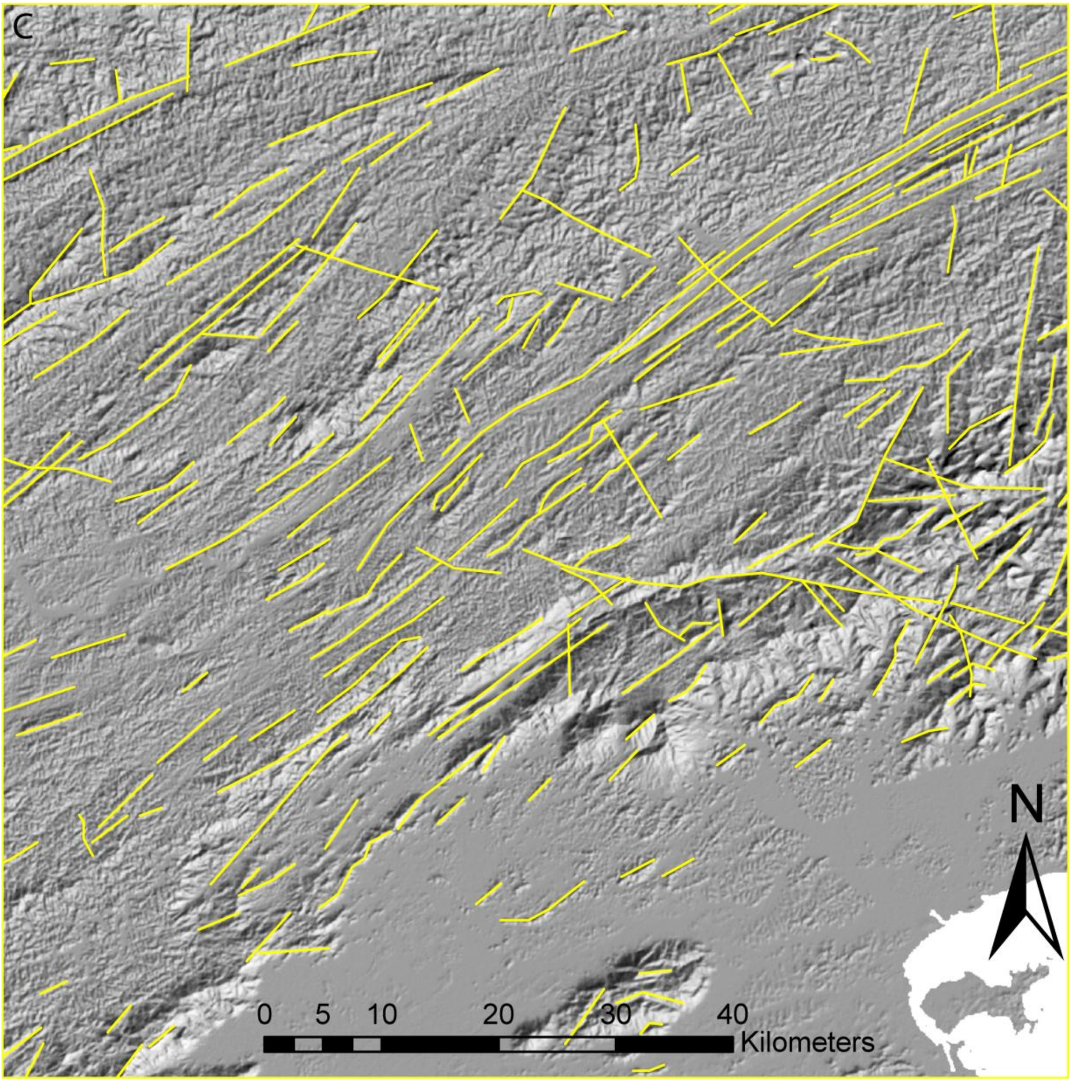
4.2 Methodology

Four different hillshades artificially illuminated from 045°, 135°, 225° and 315° were applied to the SRTM data to visualise the topography. These angles were selected as being roughly parallel and perpendicular to the trend of the Ribeira belt in the area. Multiple illumination angles are commonly used in lineament studies, in order to reduce illumination bias. Some studies (in particular those using automatic picking methods e.g Clark and Wilson (1994)) use many more than 4 angles, but given the time frame and scale of this study, 4 angles are most appropriate. In order to assess variations on both local and regional scales, lineaments were picked at 1:3,000,000; 1:1,000,000 and 1:500,000. Rivers and other features with no apparent tectonic origin were not picked.

Lineaments were picked from all 4 angles of illumination, and the datasets were combined for analysis each lineament was picked once, even if it appeared at more than one illumination angle, as this avoids the time-consuming process of having to delete multiples of the same lineament after picking. This method suffers from the disadvantage of possibly picking artefacts of the illumination direction used to create the hillshades (Fig 4.2), although due to their relatively low intensity these tend to be distinguishable from genuine lineaments, and can be avoided at the discretion of the 'picker'. By only picking the most robust lineaments that appear at a range of angles, lineaments with a genuine tectonic origin could potentially be missed. Lineaments were picked as polylines containing a number of segments, rather than as individual and seperate straight lines. Picking in this way allows curvilinear features to be followed more closely. In my opinion, segmented lines are more representative of the underlying geology than isolated straight lines with only one segment, which will be heavily biased towards the picking of small, less significant features. The Serra do Mar region was used to establish the best set of methodologies, as described above, before the study area was expanded to cover the Ponta Grossa and Florianopolis regions (See Figure 4.1 for the approximate locations of these regions).

Figure 4.4 – The same region of hillshaded data shown at 1:3,000,000 scale (A), 1:1,000,000 scale (B), and 1:500,000 scale (C), along with lineaments picked at those scales.





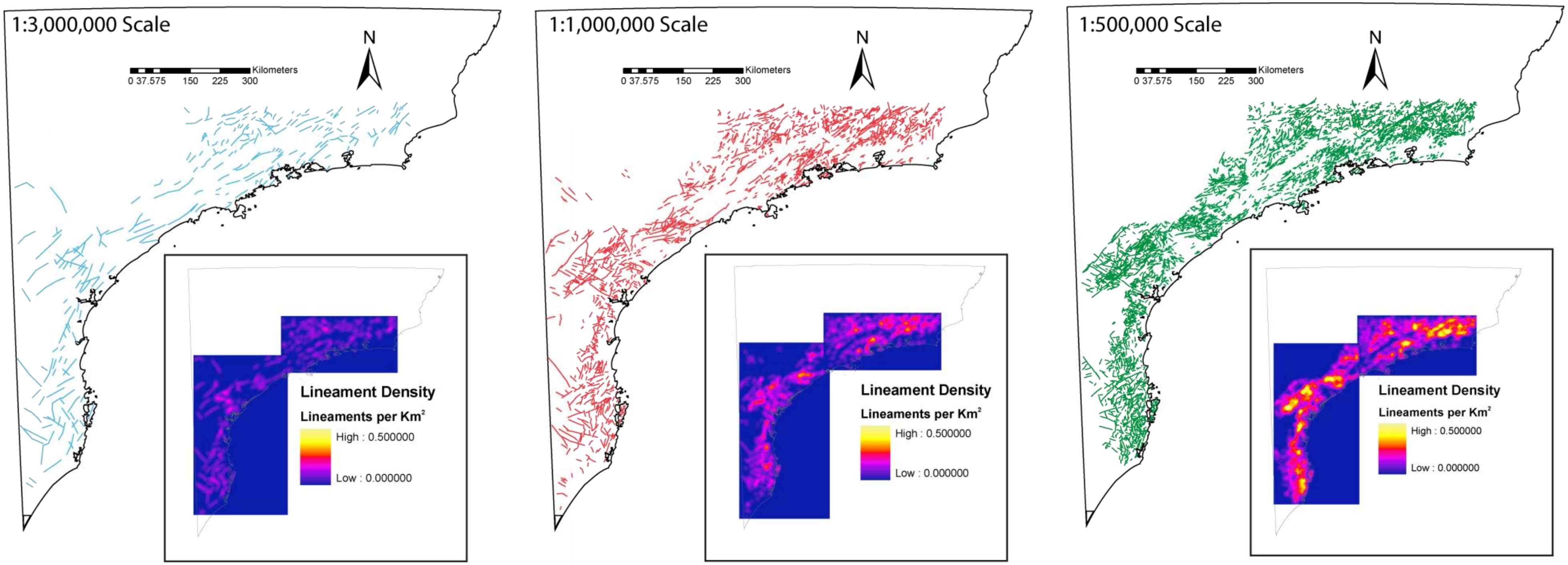


Figure 4.5. Lineaments picked from the SRTM data for SE Brazil, at 1:3,000,000, 1:1,000,000 and 1:500,000 scales. The insets show the density of the lineaments across the area. Many more lineaments are picked at smaller scales, however, lineament trends remain relatively similar, as do their density variations. Lineaments are typically less dense in the Cenozoic sedimentary basins than in the mountainous regions that surround them, due largely to the lack of topography in the basins. The Cabo Frio terrane, to the east of the area is almost devoid of lineaments at all scales.

After picking, lineaments were analysed in terms of orientation and density. To assess regional variations, lineaments were sampled by a grid constructed across the study area. Grid square size can have a large impact on the outcome of a lineament study, as large grid squares that contain more lineaments may be insensitive to local variations. Conversely, small grid squares potentially provide better local coverage, but may not sample regional trends. On this basis, the size of a grid square may be defined by the ideal number of lineaments in each square as function of the total number of lineaments and the area size. Due to variations in lineament density across the area, it was impossible to construct a grid in which every cell contained the same number of lineaments. The 'ideal' number of lineaments in a cell was set at 20, a number picked as a balance between statistical significance, and grid square size. Numbers larger than this would lead to noise in the data, making the rose diagrams difficult to interpret, whereas numbers smaller than this would lead to too few lineaments being picked, and to diagrams with insufficient data for their interpretation to be meaningful. Due to the total number of lineaments being different at different scales, larger scales have larger grid squares. I have written the following formula, which was used to determine the size of these squares:

$$Length\ of\ grid\ square\ side = \sqrt{\frac{Study\ area\ size}{\left(Number\ of\ lineaments\big/_{20}\right)}}$$

Note: this formula was used to allocate grid square size based on the ‘Serra do Mar’ study area and subsequently the same sized grid squares were used for the Florianopolis and Angola/Namibia regions. Despite lineament density varying across the area, I feel the same grid square size should be used, to enable a more valid comparison of lineament trends in the different regions.

Prior to analysis, lineaments were split by their vertices (each lineament is composed of multiple straight line segments. 'Vertices' are the points at which these segments join), to allow individual orientations of lineament segments to be analysed. Due to the curvilinear nature of many lineaments, averaging their orientation would have led to misleading or inaccurate lineament orientations. They were also split by grid square, so that lineaments in each grid square could be analysed separately. Because of this, many orientations appear in two adjacent grid squares, which could potentially weight statistical analysis and rose diagrams more towards these orientations. Since longer lineaments are far more likely to cross grid square boundaries than short lineaments, this will most likely weight towards the larger, more significant lineaments. Whilst this could be an issue, I feel that it is also the best way to capture the presence of the larger lineaments, which are not restricted to one small area onshore.

Lineament orientation was plotted using rose diagrams, and also measured by calculating mean direction and mean resultant length (Davis, 1990). The rose diagrams and statistical values were plotted on to the grid to visualise variation in lineament orientation across the area. Rose diagrams were scaled into 3 sizes according to the number of lineaments present (0-10, 10-20 and 20+ Lineaments). This allows a visual impression of lineament distribution, and also how regionally significant the trends are. A circle was divided into 16 x 22.5° segments. These segments were then coloured using 8 different colours, following a simple spectrum (see Fig. 4.6). Rose diagrams were then coloured both according to their primary and secondary lineament trends. The centre of the diagram is coloured according to the primary trend, whereas the edge is coloured according to the secondary trend. The 'gradient' tool in Adobe Illustrator (Adobe, 2007) was used to set the edge region to 20% of the radius of the rose diagram. This weights the primary trend more than the secondary trend, yet still allows for the easy visual identification of the secondary lineament trend.

Alternative methods of colouring the rose diagrams were considered, for example, the method used by Wilson et al. (2006), in which the rose diagrams are coloured similarly if their 'shape' is similar, i.e. where they both show NE-SW and NW-SE trends, they would be coloured the same way. Conversely, a rose diagram with N-S and NE-SW trends would be coloured differently, despite both the regions sharing a NE-SW lineament trend. Since throughout the Ribeira belt, NE-SW lineament trends are prevalent, whilst secondary lineament trends vary across the region, I feel that this method would not adequately represent these trends.

4.3 Results

4.3.1 Rose diagram analysis

4.3.1.1 1:3,000,000 scale

Due to the size of the grid used to select the lineaments that make up these diagrams, only a small number have been plotted (Fig 4.5). In addition, many of the rose diagrams are for the two smaller sizes, because the lineament density is relatively low. The low density reflects the large lineaments which are picked at this scale, which represent major basement structures, boundaries of large rift basins such as the Taubate Graben, and major geomorphological features such as the Paraiba do Sul River, whose morphology is consistent with rivers which are controlled by bedrock geology, and regional uplift (Summerfield, 1991). In the north of the area, lineaments trend predominantly NE-SW, parallel to the trend of the Ribeira belt. In the Florianopolis region, in the southwest of the area, NNE-SSW trending structures dominate (yellow colours). NW-SE trending lineaments are reflected by blue and purple rose diagrams within the Paraná basin, indicating that different orientations of structures were observed within the Paraná basin, compared to the orientations found in the Ribeira belt.

The primary trends are NE-SW (represented by green) in the north of the area, whilst the secondary lineament trends are more variable, with several occurrences of NW-SE trending lineaments, both in the Serra do Mar region and in the Ponta Grossa region. The NW-SE lineaments probably represent the trends of the dykes in the Ponta Grossa region, though it is unclear what they represent in the Serra do Mar region. Fractures and faults in this NW-SE orientation can be seen in my field data, which is discussed in chapter 5.

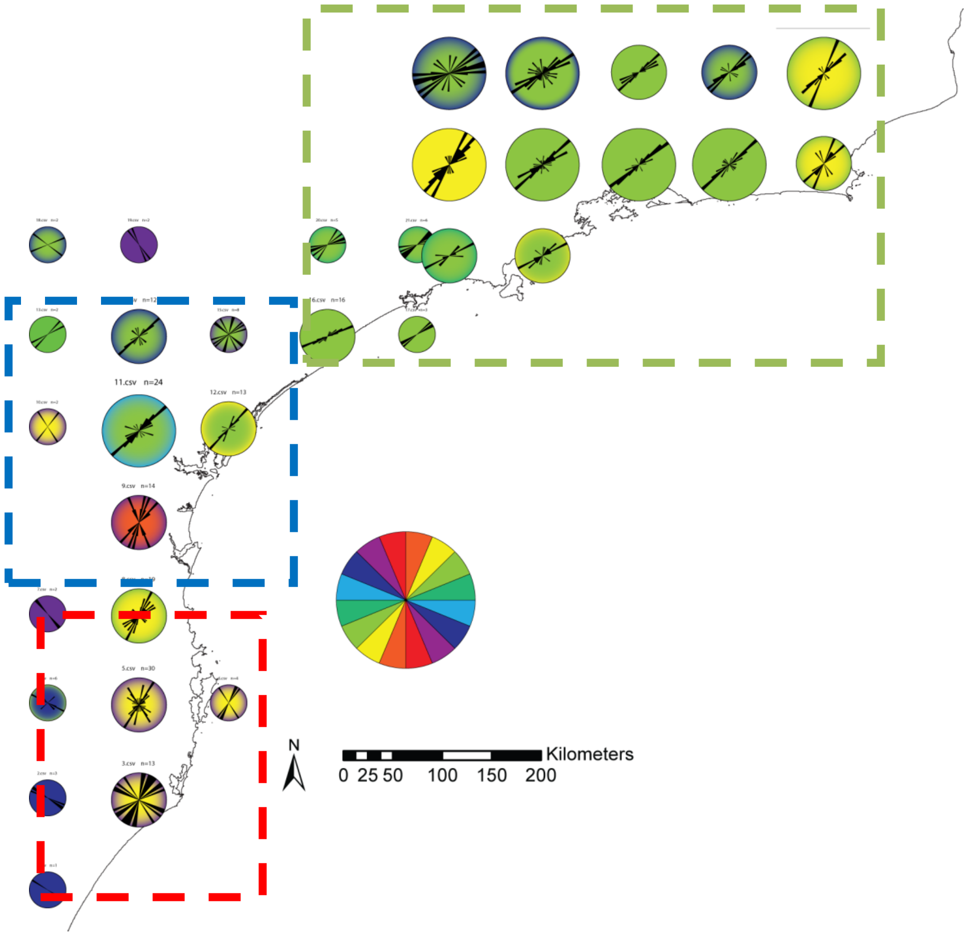


Figure 4.6– Rose diagrams for lineaments picked at 1:3,000,000 scale. Roses are coloured with the central portion corresponding to the primary lineament trend, whilst the outer region corresponds to the secondary trend. The location of the Ribeira belt is clear (Green dashed Box) with mainly green rose diagrams. These become yellow to the east, as the lineaments trend further north. Many of the diagrams to the west contain fewer than 10 lineaments, and their interpretation should be made with care as a result. The dashed boxes represent the Lineament Domains which can be seen at all scales. The Serra do Mar domain (green dashed box), the Ponta Grossa Domain (Blue dashed box), and the Florianopolis Domain (Red dashed box) can be distinguished by their lineament trends.

4.3.1.2 1:1,000,000 scale

At this scale, a much larger number of lineaments were picked and plotted (Fig. 4.7). Much more distinction between the Serra do Mar region, the Ponta Grossa region, and the Florianopolis region can be drawn at these scales. The primary lineament trends are still predominantly NE-SW (green) throughout the Serra do Mar region, although there is much more diversity amongst the secondary lineament trends. Many NW-SE and NNW-SSE (red, purple and blue) trends can be seen throughout the Serra do Mar region. Some of these probably represent the dykes documented by Guedes et al (2005), and others may represent features such as transfer zones (chapter 3.3.2), Riedel shears, or multimodal fracturing which are often associated with oblique deformation (chapter 3.2). Without ground-truthing these structures, it is impossible to say which structures form individual lineaments (see 'Ground truthing', later in this chapter).

In the northwest of the area, NE-SW trends are still present, but are often secondary trends. NW-SE trends are much more significant here, consistent with the location of the 'Ponta Grossa arch' (see chapter 2.4). The NE-SW trends recorded here represent the western extent of the Ribeira belt, and show that basement fabrics and structures are consistently NE-SW trending, whilst many lineaments, some of which are faults and dykes, crosscut it.

In the south of the area, in Santa Catarina state, NNE-SSW and NNW-SSE trends are more common at this scale. The extent of the Paraná basin can also be identified from its very different lineament orientations (it does not show the green, NE-SW trend typical of the Ribeira Belt), compared to those located in basement closer to the coast. The NNE-SSW orientations probably reflect structures associated with the Florianopolis dyke swarm, although many orientations here may also relate to fabrics and shear zones in the Dom Feliciano belt basement, or structures within the Florianopolis batholith.

Lineaments at this scale are rare within the post-rift sedimentary basins, and areas near the coasts, due to their very subdued topography. Those which are present do not display any distinct or consistent trends, when compared to those picked in the more rugged, mountainous regions.

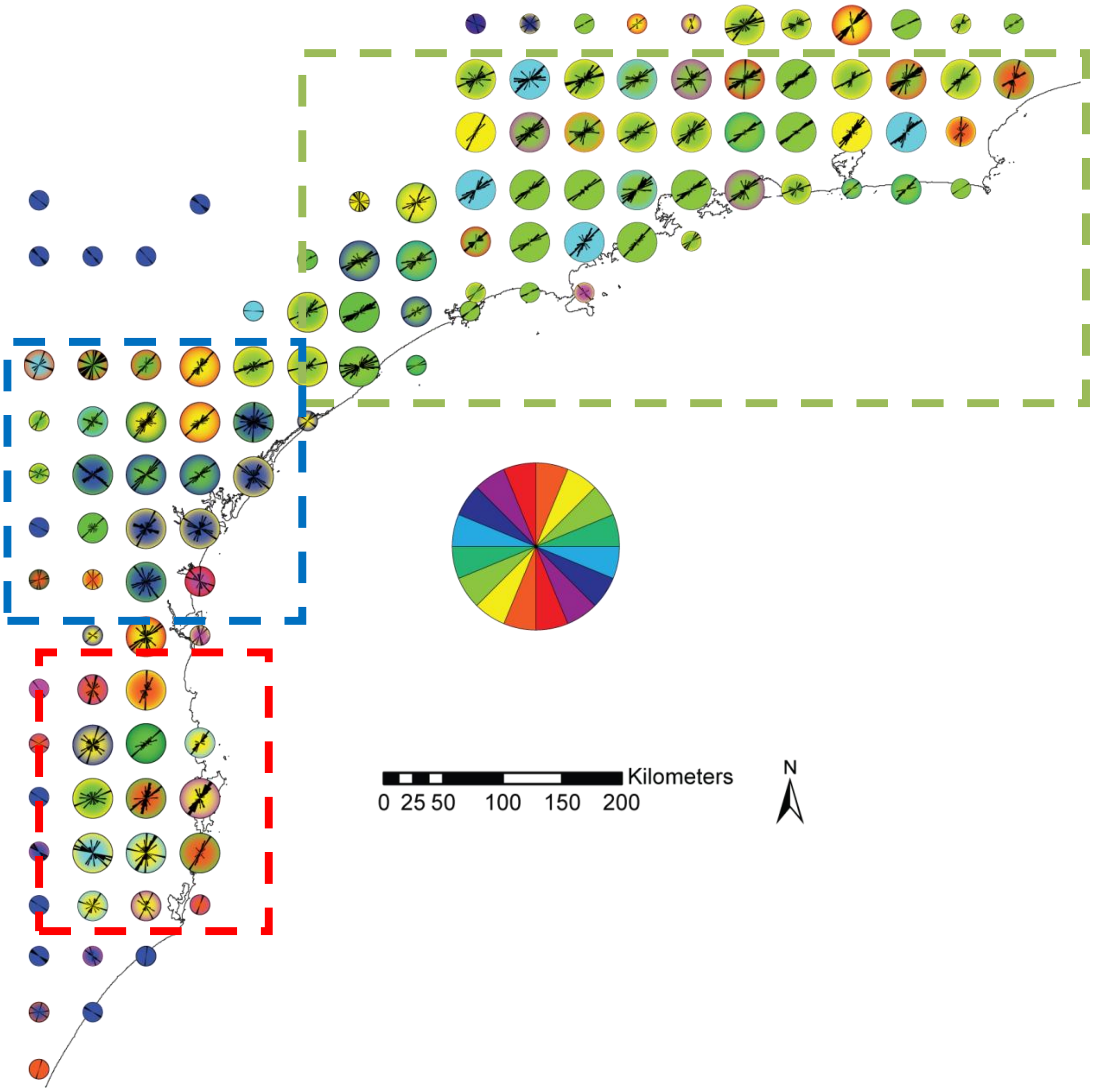


Figure 4.7 – Rose diagrams of lineaments picked at 1:1,000,000 scale. The Ribeira belt is still clear at this scale, though many different secondary trends can be seen at this scale. At the south-western end of the belt, dark blue rose diagrams are much more common, indicating NW-SE lineaments. To the south of the area, the Florianopolis region shows more N-S lineament trends, represented by red and orange colours in the rose diagrams. The Paraná basin can clearly be distinguished here, as lineaments trend NE-SW, showing as blue rose diagrams. The Serra do Mar domain, the Ponta Grossa domain and the Florianopolis domain are highlighted by green, blue and red dashed boxes respectively.

4.3.1.3 1:500,000 scale

Lineaments picked at this scale are typically shorter and more numerous than those picked at larger scales (Fig 4.8). The lineament coverage is denser, and these are the ones that have a best chance of being ground-truthed in the field. Unfortunately, these lineaments are also the ones that are most likely to have been influenced by the illumination direction of the hillshaded data, and are therefore more prone to bias.

Whilst the grid size is much smaller at this scale, and a larger number of rose diagrams are needed to display the data, the size of the resulting plots is more uniform, reflecting the more even distribution of data picked at this scale (Fig 4.8). Smaller rose diagrams reflecting fewer lineaments tend to be found closer to the coast. These coastal plains are common across the region, with the bulk of the uplift in the area occurring several tens of kilometres inland, with a majority of post-rift sediments outcropping closer to the coast (Zalán and Oliveira, 2005).

Much more diversity can be seen amongst the secondary trends of the Ribeira belt, where the primary trend is almost always NE-SW trending. Towards the east of the area, the primary trends are predominantly shaded green (NE-SW), whereas to the west, yellow shading of primary and secondary trends is more common, suggesting that the basement structures possibly trend closer to NNE-SSW in this area. Throughout the Serra do Mar region, secondary lineament trends are variable, with some adjacent regions showing sub-parallel lineaments and others showing lineaments at high angles to each other. Whilst the primary basement fabric and the trends of rift-related, and post rift structures consistently trend NE-SW, there is significant heterogeneity amongst secondary lineament orientations. Some of these lineaments, particularly in the centre of the Serra to Mar are probably the dykes and faults described by Guedes et al (2005). Some authors have hypothesised that these may be onshore continuations of NW-SE trending transfer zones (de Souza et al., 2009). These may simply be manifestations of complex strains and multimodal faulting formed during regional transtension, although without geological evidence, the kinematics and timings of these structures will only be speculative.

At the western end of the area, very different lineament trends can be seen. In the coastal region of Paraná state, NW-SE trends are dominant, with secondary trends typically being NE-SW. This region corresponds with the Ponta Grossa arch, and the NW-SE trends almost certainly represent the Ponta Grossa dyke swarm and associated faults (see Chapter 5).

South of the Ponta Grossa arch, lineaments trend NNE-SSW and SSW-NNE (orange and red, respectively). This is consistent with lineaments picked in the same region at 1:1,000,000 scale. These lineaments probably represent the dykes, faults and fractures associated with the Florianopolis dyke swarm (see Chapter 5). Since much of this region is covered by the Florianopolis batholith, few of the lineaments here are likely to represent basement foliation. NNE-SSW trending basement structures within the Dom Feliciano belt basement may, however, be responsible for many of these lineament trends (see chapter 2.3.1.2).

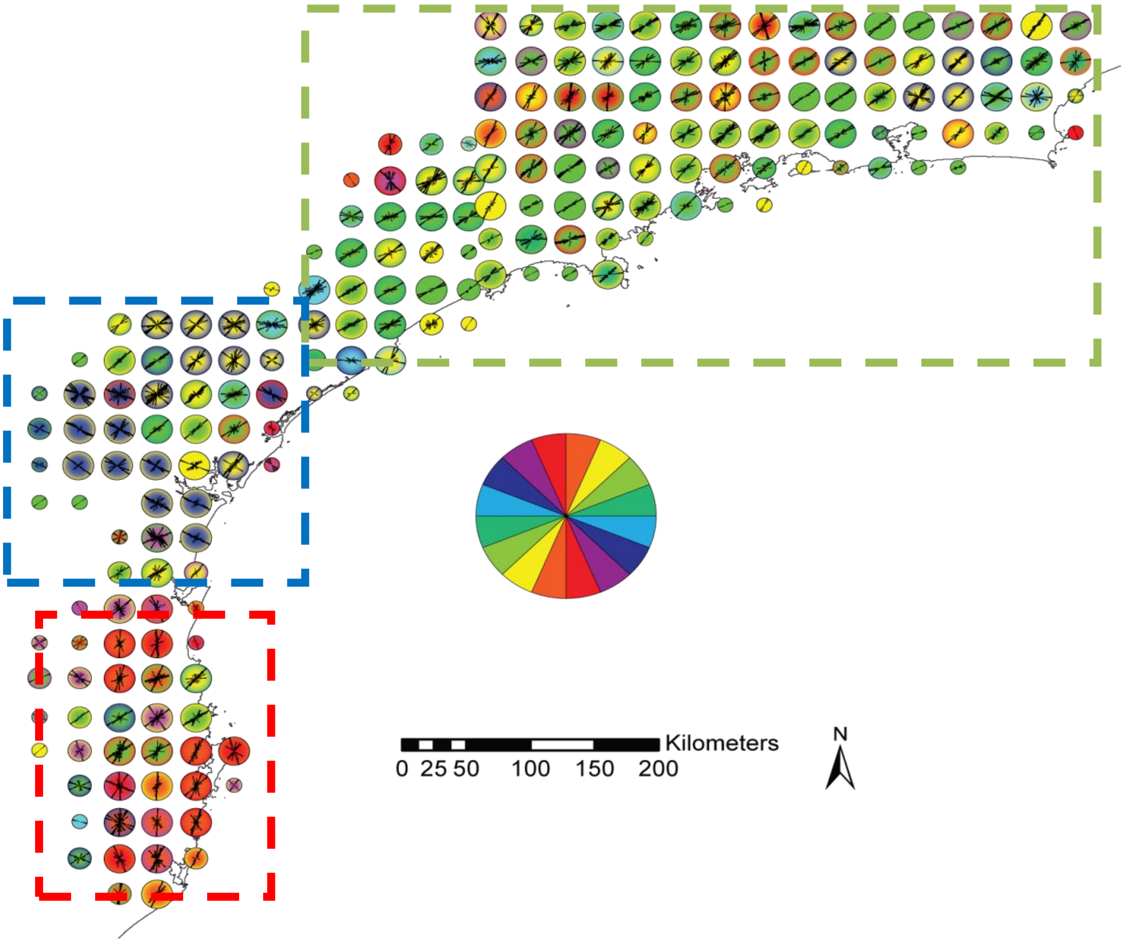


Figure 4.8 – Rose diagrams of lineaments picked at 1:500,000 scale. The three lineament zones are much clearer on this image. In the north, the Serra do Mar region (Green dashed box) contains mainly green, and some yellow centred rose diagrams. Differences between secondary lineaments in adjacent diagrams show the diversity of lineament trends in this region. The Ponta Grossa region (Blue dashed box) consists of blue and yellow rose diagrams, highlighting the NE-SW trending basement and NW-SE trending dykes. The Florianopolis region (Red dashed box) shows dominantly NNE-SSW, N-S and NNW-SSE trending lineaments.

4.3.2 Statistical analysis

Mean direction, and mean resultant length were calculated at the 1:50,000 scale to show variations across the margin (Fig.4.9). The data for mean resultant length shows scattered distributions. The majority of squares towards the coast of the Serra do Mar region show vales close to 1, highlighting the effect that picking relatively few lineaments can have on mean resultant length. The remainder of squares show values nearer to 0.5, reflecting the multiple orientations of lineaments.

Towards the southwest of the area, mean directions trend more towards N-S than those in the Serra do Mar region. In the latter area, only limited variability amongst lineament trends can be seen, other than in those areas with few lineaments. This highlights a key weakness in using mean direction for lineaments where there are a number of orientations. It is clear that the mean direction statistic is limited by being insensitive to subtleties within the lineament trends. Since only the mean is being picked, it is unclear whether all of the lineaments trend in the same direction, or whether they are spread out. This technique also allocates the same significance to areas where there are a large number of lineaments and those where there are very few. Variation across the area, which can be seen, is difficult to interpret for these reasons. Whilst the mean resultant length offers some insight into the scatter present in the data, with high values representing regions where all lineaments trend in different directions, it is similarly insensitive to the number of lineaments present, and also does not provide any information about lineament trends.

The two datasets could be viewed together, to show where lineaments showing certain mean directions are closely aligned. However, this method has little to offer in the way of identifying secondary variations, which are particularly important in the northern part of the study area, where the majority of lineaments trend NE-SW. For these reasons, I believe that the rose diagrams, although suffering from the potential for bias caused by manual colouring and interpretation, are a superior method for the analysis of lineament trends across the area.

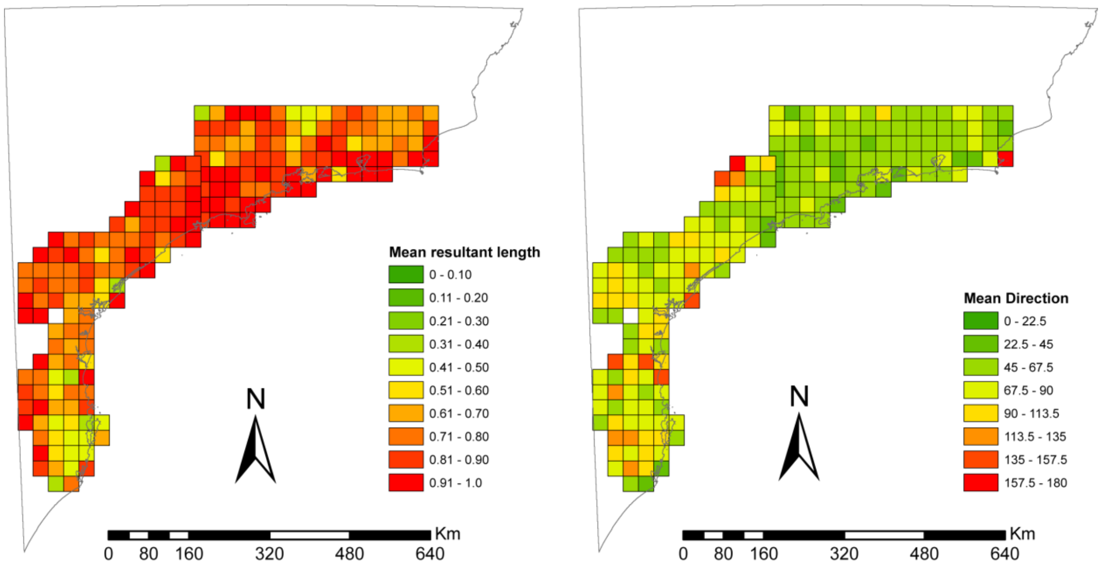


Figure 4.9 – Statistical data for lineaments picked at 1:500,000 scale. The boxes used are the same as the grid used for lineament analysis. The figure on the left shows mean resultant length: a measure of variance in lineament trend, where 1 is the lowest degree of variance, and 0 the highest. Based on this, lineaments in the Ribeira belt in both the Ponta Grossa and Serra do Mar regions cannot be easily distinguished, although the Florianopolis region appears different, with lower values of mean resultant length. The variation seen in the Ribeira belt reflects the diverse secondary lineament trends identified by rose diagrams. The figure to the right shows results for mean direction, plotted between 0 and 180°. Again scatter can be seen within the Serra do Mar region, and whilst this can be distinguished more easily from the Ponta Grossa region; the latter, however, cannot be clearly separated from the Florianopolis region. Whilst both of these diagrams can be used together to identify these lineament regions, they lack information about the actual trends of multiple lineaments in the grid square, which can more easily be identified using rose diagrams (Figs.4.4-6).

4.3.3 Ground-truthing lineament trends

There can be little doubt that lineament studies can shed light on the geometries of basement and brittle structures on the Brazilian margin. However, without ground-truthing, it is difficult to establish which lineaments are basement structures and which are faults or dykes. During fieldwork in Brazil (see Chapter 5), the lineament dataset was used in order to try to identify individual structures. Due to the nature of the terrain in the region, with steep valleys and hills covered in rainforest, this proved impossible in many areas. Although individual lineaments were visited, it was rare to find sufficient outcrop quality to clearly and unambiguously say what lineaments actually are. One main exception occurred at Quatis where a large brecciated fault zone apparently reactivates a basement mylonite and produces a very prominent NE-SW-trending linear valley. Other regions, such as the Paraiba do Sul River, do show basement fabrics and structures (such as shear zones) trending parallel to lineaments. On the scale of the margin, ground-truthing individual lineaments was impractical, and potentially misleading because the identification of one NE-SW lineament as, say, a reactivated fault zone does not mean that all features with this trend have the same origin.

Although the identification of individual lineaments has proved problematic, the trends of structures mapped on coastal outcrops throughout the area typically conform to the overall lineament trends seen in the above analysis. It may be inferred from this observation that many of the lineaments picked share orientations with brittle structure, and that some of them are rift-related. It is, however, difficult to say which lineaments are rift-related, given the large number of post-rift events which have taken place on the margin (see chapter 2.4.2), and the similarity in map-view orientation between brittle and ductile structures.

4.4 Discussion

Lineaments appear to show similar orientation patterns at all scales, and three dominant regions, corresponding to the Serra do Mar region, the Ponta Grossa region, and the Florianopolis regions can be identified. These regions correspond to the locations of major regional dyke swarms (Coutinho, 2010), and their related structures (see Chapter 5).

The strong parallelism between the trends of the Ribeira belt and later onshore rifts has been used by previous authors to suggesting that basement structures are later reactivated during brittle events (see 2.4 for discussion of this). While this lineament study provides evidence for strongly consistent NE-SW lineaments in the Serra do Mar region, it has also highlighted that a large number of lineaments deviate from this trend in geographically distinct regions. The Serra do Mar region and Ponta Grossa region both contain the NE-SW trending basement of the Ribeira belt, explaining much of this NE-SW trend in the lineament data, but there are also dykes and post-rift faults that also trend in this direction (Coutinho, 2008; Zalán and Oliveira, 2005). In the Florianopolis region, basement structures trend NNE-SSW, possibly explaining some of the lineament trends observed in this study, whilst the NNW-SSE trend may relate to faulting and/or dykes.

When making interpretations about the trends of structures mapped using lineament analysis, it is important to consider the third dimension. Published cross sections of ductile basement structures show considerable structural complexity in terms of structural style and dip; both within and between terranes (see chapter 2.3). High angle normal or oblique faults seem to be the dominant structures relating to the brittle tectonics. Although the lineaments appear strongly parallel in map view, in the 3rd dimension, the relationship may be far more complex. Parallel lineament trends do not necessarily mean that structures are directly reactivated. Fieldwork is necessary to test this idea (see Chapter 5).

Due to the parallel strikes shown by many brittle and ductile structures in this area it can be difficult to separate rift-related structures from either basement or post-rift structures. Comparing these lineaments to previous geological mapping it is possible to identify the origin of some features, such as large scale shear zones and some Cenozoic faults, although most lineaments are below the scale of available maps (eg. 1:1,000,000 (Schobbenhaus, 2007), or 1:3,000,000 (Bizzi et al., 2003)). The N-S trending lineaments in the centre of the Serra do Mar region correlate well with faults and dykes (Guedes et al., 2005), but it is difficult to establish whether the ENE-WSW lineaments in the Serra do Mar reflect brittle or ductile deformation features. Regardless of this, the strong parallelism between the Cenozoic basins onshore and the Ribeira belt suggests that both brittle and ductile events are related in some way to the NE-SW lineaments that are prevalent across the margin. The similarity between the location of lineament zones and the mapped location of the dyke swarms also suggests that syn-rift events can be identified by lineament analysis, and these events have played a key role in defining modern day geomorphology across the margin.

4.5 The African Margin

The regional effects of, and responses to, Mesozoic rifting, are not restricted to the Brazilian margin. Analysis of the conjugate margin has the potential to further enhance our understanding of the rifting process in and around the Santos basin. For this reason, I also analysed lineaments from the onshore regions of the Kwanza and Namibe basins in Africa. This study has the potential to identify structures present on both margins, and also structures which only formed on one side of the basin. The Ponta Grossa arch, for example, has been hypothesised to correlate with the Mocamedes arch in Angola (Alberti et al., 1999). This would suggest that the 'triple junction' model (Coutinho, 2008) does not apply, as the Ponta Grossa arch would have continued across the basin, as opposed to making up one of three rift arms. Furthermore, the identification of similar lineament geometries in Africa and Brazil would suggest that the same structures forming lineament geometries in Brazil also potentially formed them on the African margin.

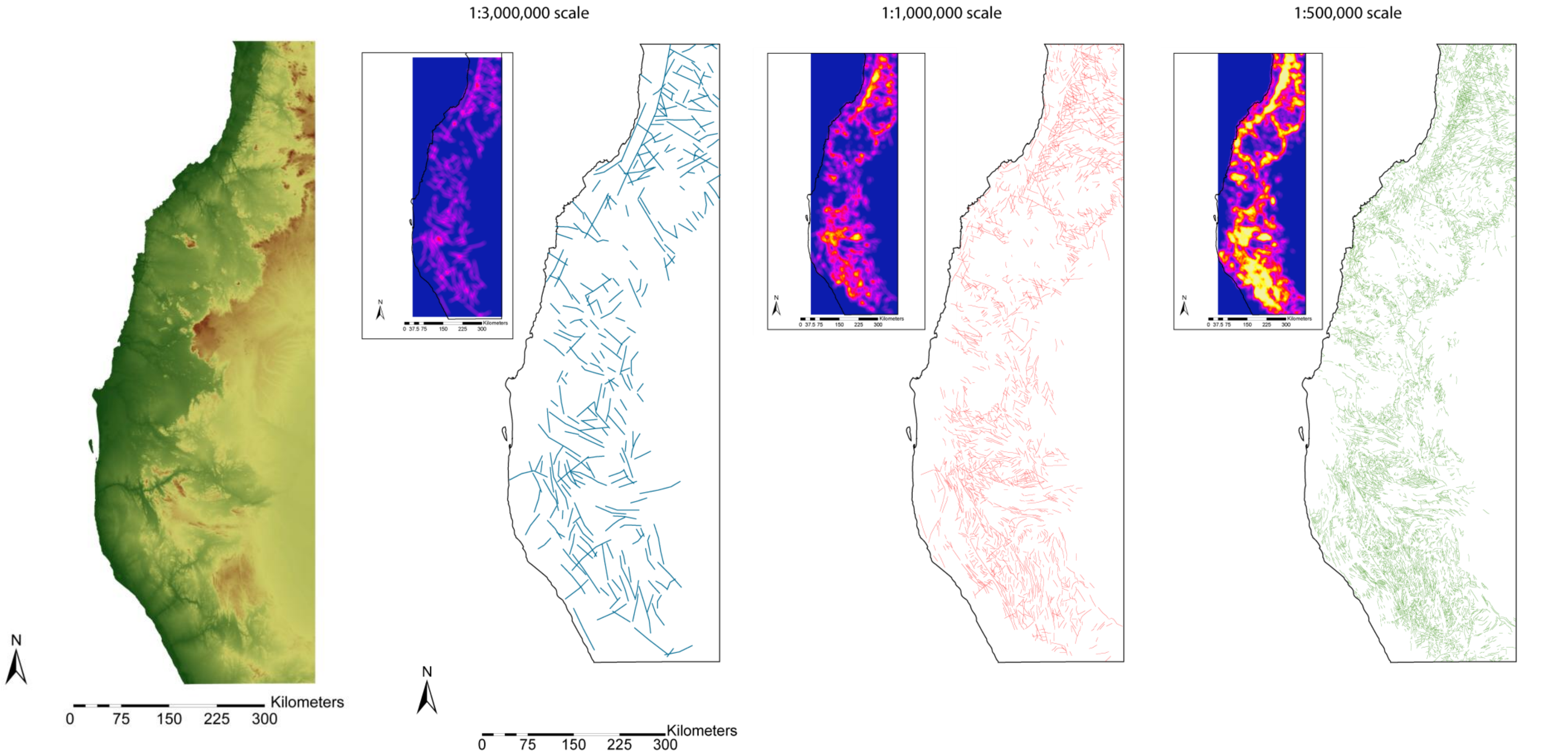


Figure 4.10 – The data used (left), and lineaments picked at all scales from the African dataset. The uplifted area seen on the topographic dataset corresponds with the Great Escarpment, a coast-parallel uplift, formed several million years after breakup (Gallagher and Brown, 1999). Lineaments show similar density distributions at all scales. The 1:500,000 dataset shows many more lineaments, reflecting the higher resolution at which these lineaments were picked.

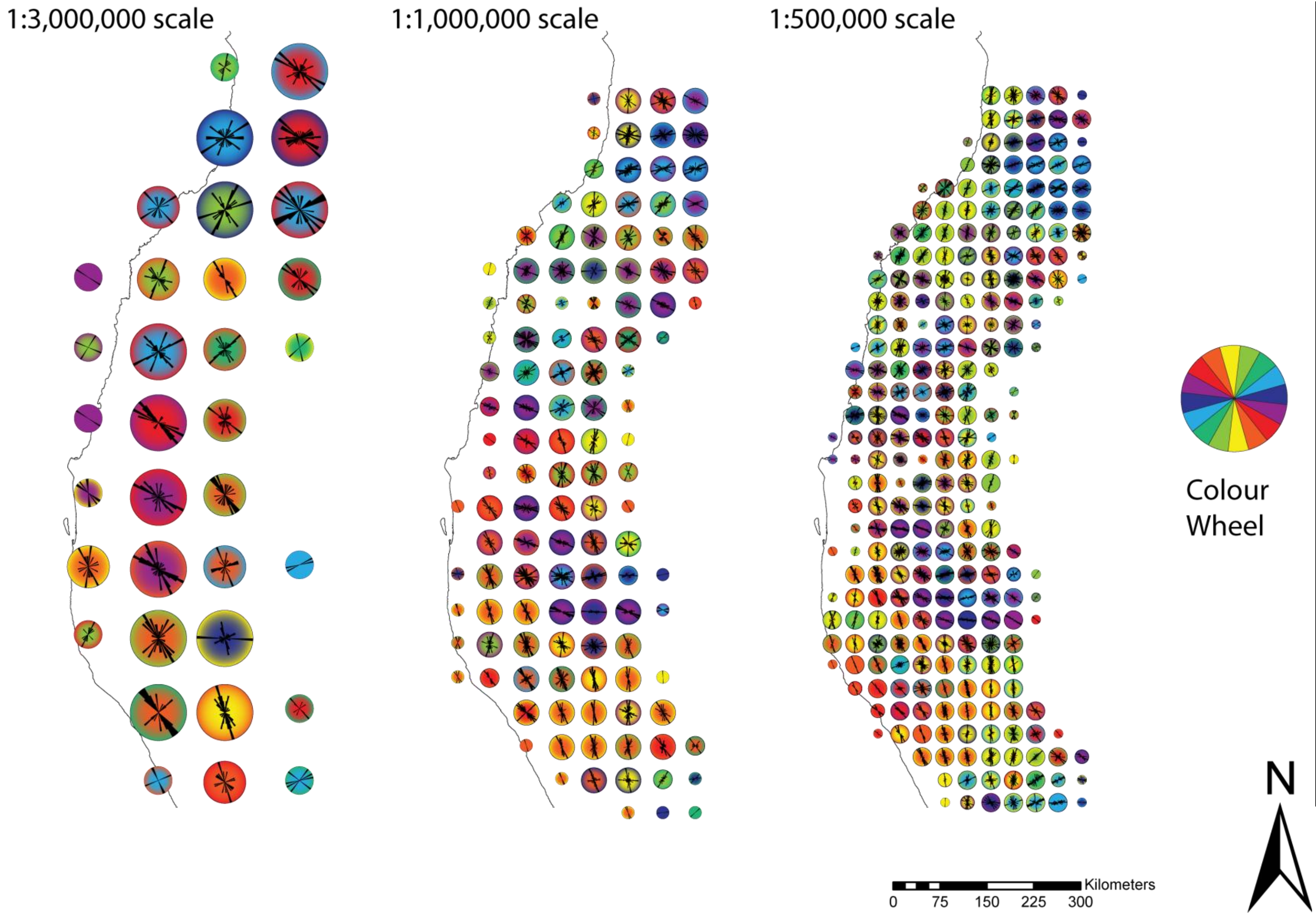


Figure4.11 – Rose diagrams of lineament data from the African margin, coloured by orientation. Note the rotated colour wheel relative to the South American margin. This is to enable easier correlations when these lineaments are restored to an early rift orientation (see Fig. 4.11). Similarly to lineaments seen in the South American dataset, two lineament domains can be identified. One, to the north of the area contains mainly green and yellow rose diagrams, indicating roughly N-S trending structures. The other, to the south of the area contains yellow, orange and red rose diagrams, indicating NW-SE trending structures.

Lineaments were picked from the African SRTM data, using the same methodology that was used for the Brazilian lineament study, with four hillshades orientated at 90°, and lineaments picked at 3 scales (Fig. 4.10). Rose diagrams were plotted (Fig. 4.11) and then rotated, together with the lineaments to the reconstructed 135 Ma position of the African margin relative to the South American margin (Fig. 4.12). To achieve this, Gplates software (Gurnis et al., 2011) was used to reconstruct the geometry of the South Atlantic at 135 Ma, keeping the present day orientation of the South American margin fixed. The 135 Ma timeframe was chosen as this represents the earliest rift stage, as well as the timing of the dyke intrusion into the Brazilian margin, and also the period when the earliest faults would have been developing in the offshore basin (Karner and Driscoll, 1999). It is also several million years prior to breakup, and therefore is the period when features are most likely to have developed on both margins simultaneously. There are a number of well documented issues related to plate reconstructions in the South Atlantic (Aslanian et al., 2009; Torsvik et al., 2009). These include: the correct fit of the ocean continent boundaries; the amount and locations of hyperextension; and the timing of breakup. However, the approximate fit given by Gplates is suitable for correlating such large-scale lineaments.

4.5.1 Lineament Data - African Margin

The lineament data collected from the African margin compares well across all scales in terms of lineament density (Figs 4.10 and 4.11). Lineament orientation compares well between the 1:1,000,000 scale and 1:500,000 scale lineaments, but in the north of the region, the 1:3,000,000 scale lineaments show more NE-SW trends, compared to the NNE-SSW trends observed at smaller scales. Lineament density is variable, with the highest densities observed in the south of the area at all scales. To the north, large areas with very few lineaments exist, and and were observed at all scales (Fig. 4.10).

Zones of NNE-SSW trending lineaments to the north of the area were observed towards the coast. To the south of the area, NNW-SSE and NW -SE trending lineaments were mapped, again, across all scales. Inland, large numbers of E-W and ESE-WNW trending lineaments, which have quite different orientations to those lineaments were observed nearer to the coast. At least two broad lineament domains can be identified, the first is to the north of the area and contains mainly green and yellow coloured rose diagrams, with some blue, indicating NNE-SSW and NNW-ESE primary and secondary lineament trends. The second domain is clear at all three scales, and consists of yellow and orange coloured rose diagrams indicating NNW-ESE and NW-SE primary and secondary trends.

4.6 Reconstructed data - Discussion

Two of the three lineament zones identified on the South American margin can also be seen on the African margin when restored to 135Ma. The Florianopolis lineament trends are particularly well developed on the Namibian margin, highlighting both the basement similarity between the Dom Feliciano and Kaoko belts, and also that faults, fractures and dykes are likely to be present in similar orientations on each side of the Atlantic. This hypothesis needs to be integrated with field data on the African margin, since much of the correlation between lineament domains may be related to correlative basement units, structures or fabrics, as opposed to brittle structures. Dykes are thought to intrude parallel to basement in the African margin (Coutinho, 2008), supporting the view that brittle structure is recorded in many of the lineament orientations.

The NE-SW Serra do Mar lineament zone also correlates well, with an elongate area of green and yellow rose diagrams in the north of the African study area. This again is likely to be due to correlation between basement features on either side of the Atlantic. The lineament zones on either margin both display the same diversity amongst different lineaments, suggesting that these lineaments may have similar origins. Unfortunately, recent field data does not exist from the Angolan margin, so comparisons between brittle structures on either side of the Atlantic are difficult to prove. Trends of structures in the offshore Kwanza basin, however, do suggest brittle structures may follow these lineament trends. Whether or not dykes intrude the onshore, and if so, whether these are influential in the development of the basins on the African margin, is unclear, and needs further research.

The Ponta Grossa arch is much more difficult to correlate with African lineaments. Whilst blue rose diagrams are present on the African margin, they do not fall in such a well-defined zone as those on the Brazilian margin, nor do they consistently align along the strike of the Ponta Grossa arch.

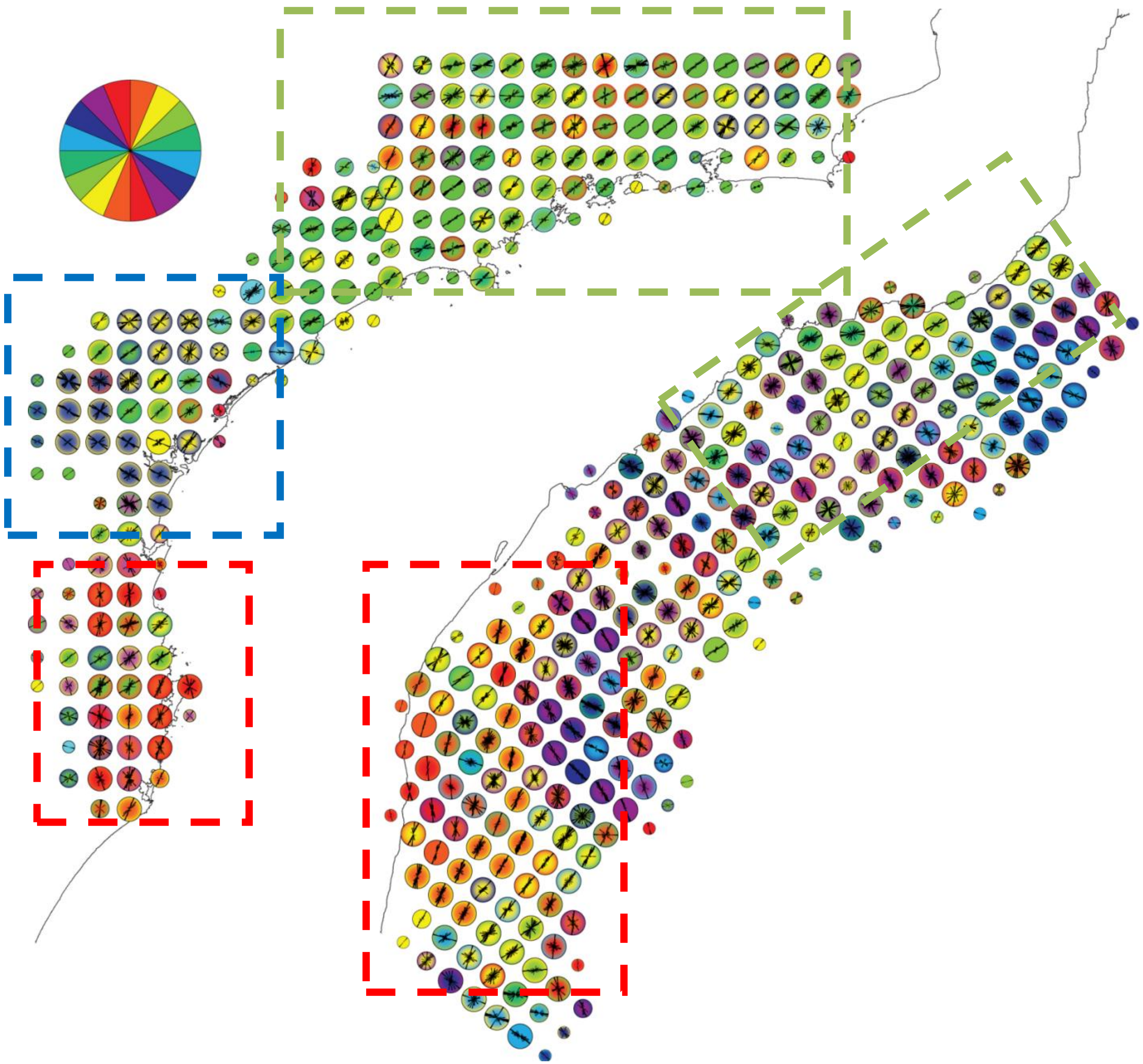


Figure 4.12. Rose diagrams at 1:500,000 scale, for the South American and African margins (see figures4.7 and4.20). The present day coastlines of south-eastern Brazil and south-western Africa have been restored to their position 135 Ma, in a syn-dyke, early syn-rift orientation. The green rose diagrams of the Serra do Mar region to the top right of the image can be correlated with similar lineament trends on the Angolan margin (green dashes). Similarly, lineaments in the Florianopolis region in Brazil can be correlated with lineaments in northern Namibia (red dashes). The Ponta Grossa arch (blue dashes) is more difficult to correlate. Although purple and dark blue rose diagrams on the African margin suggest similar orientations are present (when the margins are restored to 130Ma), they form a diffuse zone, which is consistent with the location of the uplifted hinterland, formed during the Cenozoic. This zone is inconsistent with the narrow, well defined zone on the Brazilian margin. The region directly ‘opposite’ the Ponta Grossa region also contains few yellow or dark blue lineaments in the coastal region, suggesting that the Ponta Grossa arch cannot be correlated easily across the South Atlantic.

Differences between the geomorphology of the Brazilian margin and the African margin could be responsible for some of the lack of some correlations. Further inland, lineament trends in Africa appear different to those at the coast. This may be due to the inland regions having been uplifted during the formation of the African Great Escarpment, during the late Cretaceous and early Cenozoic (Gallagher and Brown, 1999). This event led to the uplift of much of central southern Africa, and the reorientation of drainage patterns (Moore, 1999). It is possible that these drainage features, and other geomorphological features, such as the inland deserts of southern Africa may play a greater role in governing the morphology of lineaments compared to basement fabrics and brittle structures.

Correlations between South America and southern Africa can be drawn using these lineament datasets, however, without field data it is difficult to test more precisely how these lineament geometries relate to structures formed during the rifting of the South Atlantic. Field evidence for faults, fractures and dykes showing similar geometries to lineaments picked is presented for the South American margin (Chapter 5), suggesting that these lineaments may be rift related, but without similar field evidence for the African margin, this is speculative.

4.7 The effectiveness of lineament analysis

In the present study, lineament analysis has proved effective at identifying structural trends associated with major dyke swarms, illustrating that rift related structures can be identified and studied using remote-sensing techniques. A number of difficulties encountered highlight the need for further data, and careful thought when studying and interpreting lineaments.

Multiple scales were used, and show both links with each other, and with field data. It is, however, difficult to apply conclusions from this lineament study to any, but the largest structural features. Field study on an outcrop scale is unlikely to either detect or identify features at this scale, and links between lineament orientations and structural orientations can not be used in isolation as clear evidence that particular lineaments represent particular structures. Whilst ground-truthing individual lineaments can improve links between field data and lineament data, it has proved difficult to find lineaments to ground-truth. Additionally, on the scale of the region studied, identifying individual lineaments would be impractical and time consuming.

Lineament analysis on smaller scales, possibly using higher resolution data could in principle resolve some of these issues. However, the sheer size of such a study would again make this impractical, both in terms of the time taken to do the picking, and the handling and processing of data, both in terms of the number of lineaments and the size of the raster datasets needed to cover the same area with higher resolution data. An ideal way to resolve the inability to ground-truth individual lineaments would be to compare lineament datasets to geological mapping. Geological maps of the scale required for the Brazilian and African margins are, however, generally unavailable. This is due in part to the area size, and also the difficulty in conducting detailed geological fieldwork within the Atlantic rainforest which covers much of the Brazilian margin. Available maps, whilst detailed, are typically at a scale of 1:1,000,000 (Schobbenhaus, 2007), or 1:3,000,000 (Bizzi et al., 2003), and detail structures much larger than the majority of lineaments picked.

Without field data, identifying the origin of lineament trends is impossible. Apparent parallels between basement structures and brittle structures in map view have been suggested as evidence for basement reactivation. Basement structures and brittle structures may trend parallel, but their dips may be different (see Chapter 5) detailed field analysis is needed alongside lineament analysis in order to understand lineament trends.

4.8 Conclusions

Lineament analysis of the south-eastern Brazilian margin reveals three main lineament zones:

i) The Serra do Mar region, where primary lineaments trend NE-SW, and secondary lineaments show diverse orientations;

ii) the Ponta Grossa region, where lineaments show two main trends: NE-SW and NW-SE; and

iii) the Florianopolis region, where lineaments trend NNE-SSW and NNW-SSE.

Many of these lineament trends correspond with basement trends, but others, particularly the NNW-SSE trends in the Florianopolis region and the NW-SE trends in the Ponta Grossa region, correspond with brittle rift related structures (further discussed in Chapter 5). In the Serra do Mar region, dykes and many basement structures trend parallel to basement fabrics, and as such, it is difficult to separate such features.

Data from the Angolan and Namibian margin shows similar trends to those seen in South America, when the margins are restored to their approximate position ca 135Ma. Lineaments possibly related to the Ponta Grossa arch do not correlate well, possibly due to the regional geomorphology in southern Africa, but also possibly due to such structures not being present on both sides of the Atlantic. This seems to be consistent with what would be expected if these lineament zones are related to a triple junction centred on the north-western Santos Basin.

Methodological issues affecting the results and conclusions are apparent. The scales at which lineaments were picked are much larger than those at which field data can be collected. The choice of data used is fundamental to the lineament study, with bias integral to all data sources. An understanding of the relationship between lineaments and geological structures is crucial, but ground-truthing is hampered by the scale of the study and the vegetated nature of terrain in the study area. Lineaments in southern Africa have no field data to confirm their origin or relationships to South American lineaments.

5 Outcrop scale processes and relationships

Introduction

Geological fieldwork and field data provides a critical understanding of the three dimensional geometries of brittle structures onshore, their relationship with basement structures and fabrics, their kinematics, and age relationships relative to the early opening of the south Atlantic Ocean. The geometries of these structures may then be used to ascertain whether lineament data (see chapter 4) provides a reliable representation of the pattern of brittle structures across the margin. These outcrop-scale structures are linked geometrically, spatially and temporally with offshore data in an attempt to understand the influences on the development of structures in the Santos basin. These analyses will be covered briefly in this chapter, and further in Chapter 7.

Field observations and geometrical data are presented in this chapter for each locality, along with outcrop-by-outcrop discussion of their implications for regional tectonics, together with an appraisal of the larger scale implications of these observations at the end of each section, and at the end of the chapter.

5.1.1 Why field data?

The primary aim of this study is to identify influences on the development of structures in the Santos basin. Offshore seismic and gravity data and onshore lineament data provide information on the large scale relationships between brittle and basement structures and changes in geometry across the region. However they offer little understanding of the small-scale 3D geometries of structures or the kinematic development of the margin. Outcrop-scale structural studies provide an opportunity to study individual faults and fracture systems, and acquire statistically meaningful datasets on the geometry and kinematic evolution.

The field study has four main goals -

- To identify syn-rift structures

  No evidence for syn-rift faulting onshore has been published previously. An understanding of the location, geometry and kinematics of syn-rift structures onshore is crucial to the understanding of the early development of the rift, since kinematic data, and cross-cutting relationships are not available from offshore regions, and to apply this understanding to the offshore basin. A key aim therefore was to identify Early Cretaceous-age faults exposed onshore.

- To ground-truth lineament trends

  3 major lineament regions, each corresponding to the location and orientations of major dyke swarms have been identified (see Chapter 4). Fieldwork allows an assessment of whether the lineament trends observed from topographic data reflect brittle tectonics, basement structure, or both (or neither).

- To collect kinematic data and 3D geometries

  Since the margin developed obliquely to regional extension vectors, an understanding of the complex outcrop-scale structures formed during regional oblique deformation is important, in order to understand the kinematic development of the margin as a whole. An understanding of how structural geometries and kinematics may vary between the three lineament regions will aid understanding of the large-scale influences on margin formation.

- To investigate the relationship between basement structures and fracturing

  Previous studies (see Chapter 2) have assumed that the geometry of fractures and faults is influenced (or controlled) by weak Brasiliano-aged basement structures. An examination of the geometrical and spatial relationships between brittle faults and fractures, and basement structures and fabrics allows this hypothesis to be tested.

5.2 Methodology

The four main goals for the fieldwork were pursued over three field seasons. Locations were identified across the region from Buzios in the northeast, to Florianopolis in the southwest. (Fig. 5.1) Key regions, highlighted from the lineament study were visited and outcrops identified from aerial photos using Google Earth™, published literature (in particular, Coutinho (2008)) and from the local knowledge of Professor Julio Almeida (UERJ). Outcrops inland are typically highly weathered, with strong degrees of lateritisation, typical of thick, tropical soils. This made collection and interpretation of structural data from these regions difficult, due to ‘crumbling’ outcrops, and thick covers of vegetation and soil. Due to time constraints in covering such a large area, outcrops in coastal regions were chosen, partly due to ease of location and access compared to rainforest outcrops, but also because they are clean exposures. Due to their coastal location, these outcrops are typically widely spaced, with large beaches in between. Due to the coast-parallel nature of the basement geology, many outcrops studied expose the Rio Negro magmatic arc (described in Chapter 2)

During the first field season (2009), outcrops in the central portion of the Ribeira belt were studied. The initial aim of this study was to identify the role of Ribeira belt basement in the development of brittle structures onshore and offshore in the Santos basin. Following this, a larger-scale study was carried out during the second field season (2010) whereby outcrops from all 3 major dyke swarm domains were visited. Having been identified, outcrops were then chosen for further study on the basis of outcrop quality and extent, and whether there was significant evidence of brittle deformation.

Lineament Zone	Outcrop (or region) name	Location	Basement Terrane	Brittle structure
Serra do Mar	Praia das Focas	22°45’55”S. 41°52’43”W	Cabo Frio Terrane	NW-SE dextral faults – post rift?
	Praia Das Conchas	22°52’22”S. 41°59’00”W	Cabo Frio Terrane	Syn-rift NE-SW sinistral oblique faults and dykes intruding parallel to them
	Quatis	22°23’18”S. 44°17’13”W	Occidental Terrane	Indurated fault breccias in mylonite on border of post-rift basin
	Caraguatatuba	23°37’24”S. 45°21’25”W	Rio Negro Arc	Basement-parallel low offset fracturing
	Ponta Negra	22°57’25”S. 42°41’18”W	Cabo Frio Terrane	Basement-parallel fracturing
	Grumari	23°01’56”S. 43°28’52”W	Oriental Terrane	Dolerite dyke showing en-echelon geometry and fracturing
	Mambucaba	23°02’16”S. 44°33’07”W	Rio Negro Arc	Basement-parallel dolerite dyke and faults
	Ubatuba	23°29’09”S. 45°05’52”W	Rio Negro Arc	Syn-and post-rift dykes,-parallel fractures and faults. Local basement influence
	São Sebastião	23°49’17”S. 45°24’35”W	Rio Negro Arc	Small dyke and parallel fractures cut basement

	Guarujá	23°58’26”S. 46°11’11”W	Rio Negro Arc	Basement-parallel fracturing and dykes in shear zones
Ponta Grossa	Ilha do Mel	25°45’55”S. 41°52’43”W	Rio Negro Arc	Large dolerite dyke and parallel fracturing cut NE-SW trending basement
	Ilha de São Francisco	26°09’47”S. 45°24’35”W	Rio Negro Arc	Complex fracture sets cutting NNW-SSE trending dolerite dyke. No basement influence
	Guaratuba	25°52’12”S. 48°33’46”W	Rio Negro Arc	Dyke intruding parallel to NW-SE faults
Florianopolis	**Florianopolis**	27°35’10”S. 48°29’49”W	Florianopolis Batholith	NNE and NNW trending Fractures, faults and dolerite dykes in unfoliated granite basement

Table 5.1. The outcrops visited with locations representing the approximate centre of each outcrop or region, the basement terrane they are situated in, and a brief description of what can be observed at each outcrop.

The outcrops studied are listed in Table 5.1 and areas shown on Figure 5.1. They are grouped by ‘lineament domain’. Some of these localities highlighted in bold, such as ‘Ubatuba’, contain more than one studied site, separated in some cases by several kilometres. Variation between outcrops within these separate regions will be discussed in further detail in the ’results’ section of this chapter.

Absolute and relative dating of fracturing and faulting in crystalline basement, are impossible without geochronological data and younger rocks of a known age that either cut or are cut by the faults. For this reason, where possible, outcrops showing dykes were chosen, in order to try to ascertain relative ages for faults and fractures through observations of their cross-cutting and intrusive relationships. Many dykes across the margin have been dated (Guedes et al., 2005; Stewart et al., 1996; Turner et al., 1994), and therefore the ages of these dykes were used to infer timings for deformation. Syn-rift dykes and post-rift dykes were identified on the basis of their petrology. Syn-rift dykes are mostly tholeiitic dolerites, often with plagioclase phenocrysts and red weathering reflecting their high iron content.Younger dykes are typically alkaline lamprophyres, lack coarsely crystalline feldspar, and have abundant mica, giving them a shiny, black appearance. Obviously, since not all of these dykes have been dated, this method relies on the assumption that dykes of a similar petrology are a similar age.

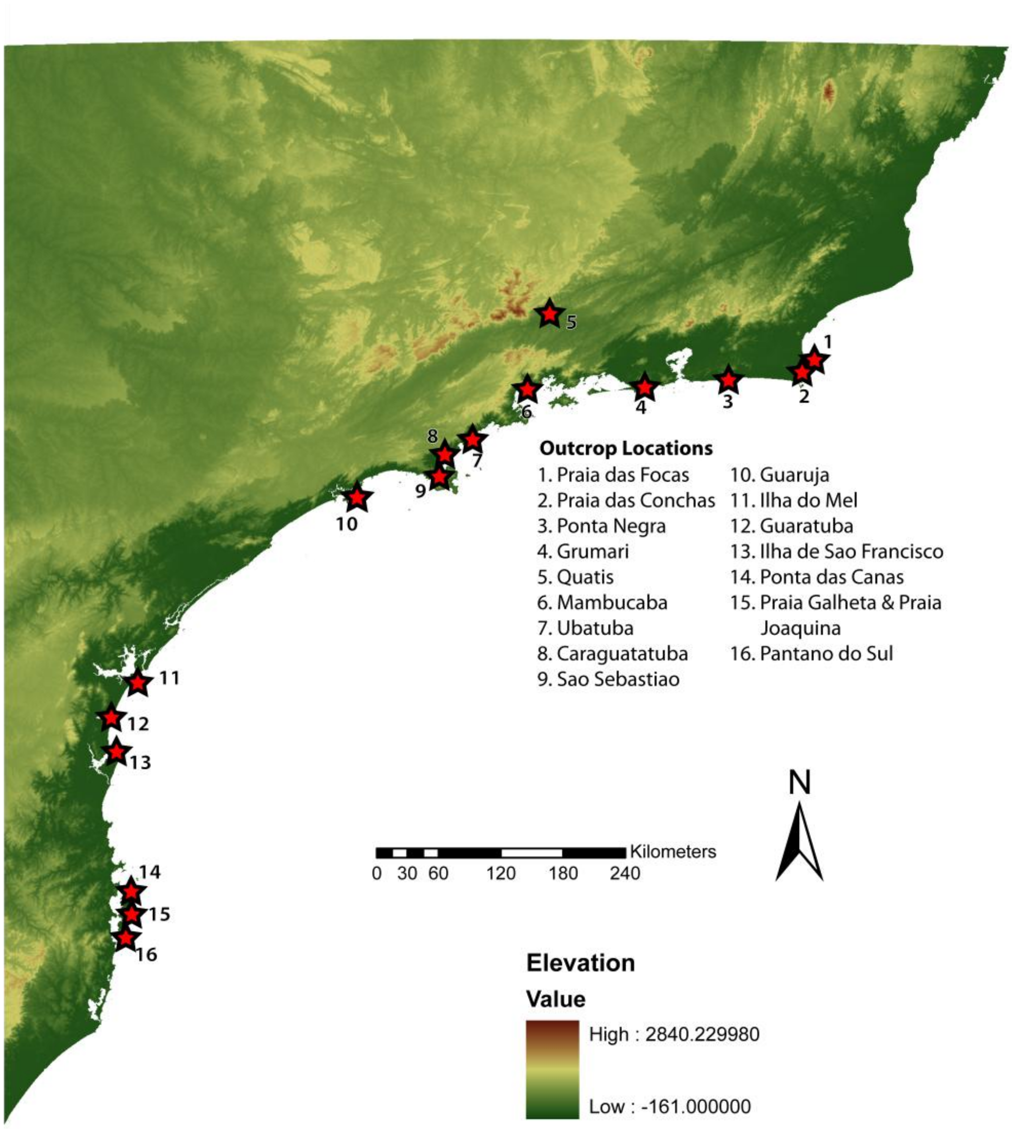


Figure 5.1 – Location map showing the regions visited in SE Brazil, using the same SRTM 90m elevation data that was used for the lineament analysis in chapter 4, coloured by elevation as opposed to hillshade.

At each outcrop, the following data and observations were collected

- Measurements of fault and fracture orientations and kinematics

        - Kinematic data, such as slickenlines, senses of offset and offset amounts were collected where possible. Observations of fault rocks and mineral fills along faults and fractures were also collected, where possible.
        - In this study, I treat faults as structures which have evidence of offset, either by observing juxtaposed features across them, fault rocks within them, or structures such as slickenlines on the fault plane. Fractures, in contrast have none of these features, although it is possible that offset across them is difficult to observe.
    - Measurements of orientations of basement foliation and structures
        - Where possible, observations were made of their relationships with brittle structures. These relationships include direct reactivation, and influence of basement heterogeneity on fault and fracture geometry.
    - Measurements of faults, fractures and intrusive structures relating to Lower Cretaceous dykes
        - Intrusive features, evidence for oblique or orthogonal opening and evidence for propagation along pre-existing fractures all provide evidence for the dyke's history and origin.
        - Where possible, age relationships, such as cross cutting relationships between dykes, faults and fractures were identified. Any evidence for apparent reactivation of dyke margins, and evidence for dykes having reactivated pre-existing structures during their emplacement was collected.

5.2.1 Data Quality

A number of issues were encountered with the quality of both outcrop and structures present at outcrop. As previously mentioned, inland outcrop was limited and often inaccessible due to dense forest. Better exposures were found at the coast, but these outcrops are separated by large expanses of beach and are difficult to correlate with one-another.

Due to the relatively low (or zero) offsets identified on many faults and fractures, cross cutting relationships cannot be observed in some cases, and where they are observed, are often ambiguous (chapter 3.2.1). Few examples of cross-cut basement structures can be identified (although some exceptions are detailed in the text and images of this chapter). Lineations on fault surfaces are rare, possibly due to the coarsely crystalline nature of many of the host rocks in the area. Where lineations are observed, they are rarely accompanied by steps or other offset-sense indicators (described in chapter 3.2.1).

5.2.2 Fault Kinematics

Kinematic indicators on faults are essential in order to assess how a region has deformed (section 3.2.1). Cross-cut basement structures are the most obvious type observed here, where offset of basement can be directly measured. Where 3D exposure of faults is present, oblique slip can also be assessed. Many outcrops in the region do not have this level of 3D exposure, and typically basement does not contain structures which are easily identified as being offset. Identification of slickenlines is also difficult, given the coarsely crystalline nature of many of the rocks, and also the weathering which has taken place on many of the fractures surfaces across the area.

5.3 Results

For each outcrop, I present a selection of representative photographs, with interpretations of geological structures, their relationships and kinematics. Data is presented in the form of equal angle stereonets, plotted using Stereo32 software (Röller and Trepmann, 2003). The first stereonets in each figure are plotted as planes (black lines) and lineations (blue arrows). Each outcrop has a small location map showing aerial photographic data from Google Earth™ software. Key outcrops also show a sketch geological map, showing the location of basement rocks (grey), dykes (red), and also geomorphological features such as vegetation (green), rubble (dotted areas) and beaches (yellow).

5.4 The Serra do Mar

Nine areas were visited across the Serra do Mar region. All of these outcrops expose parts of the Ribeira belt, in a variety of terranes and different basement lithologies.

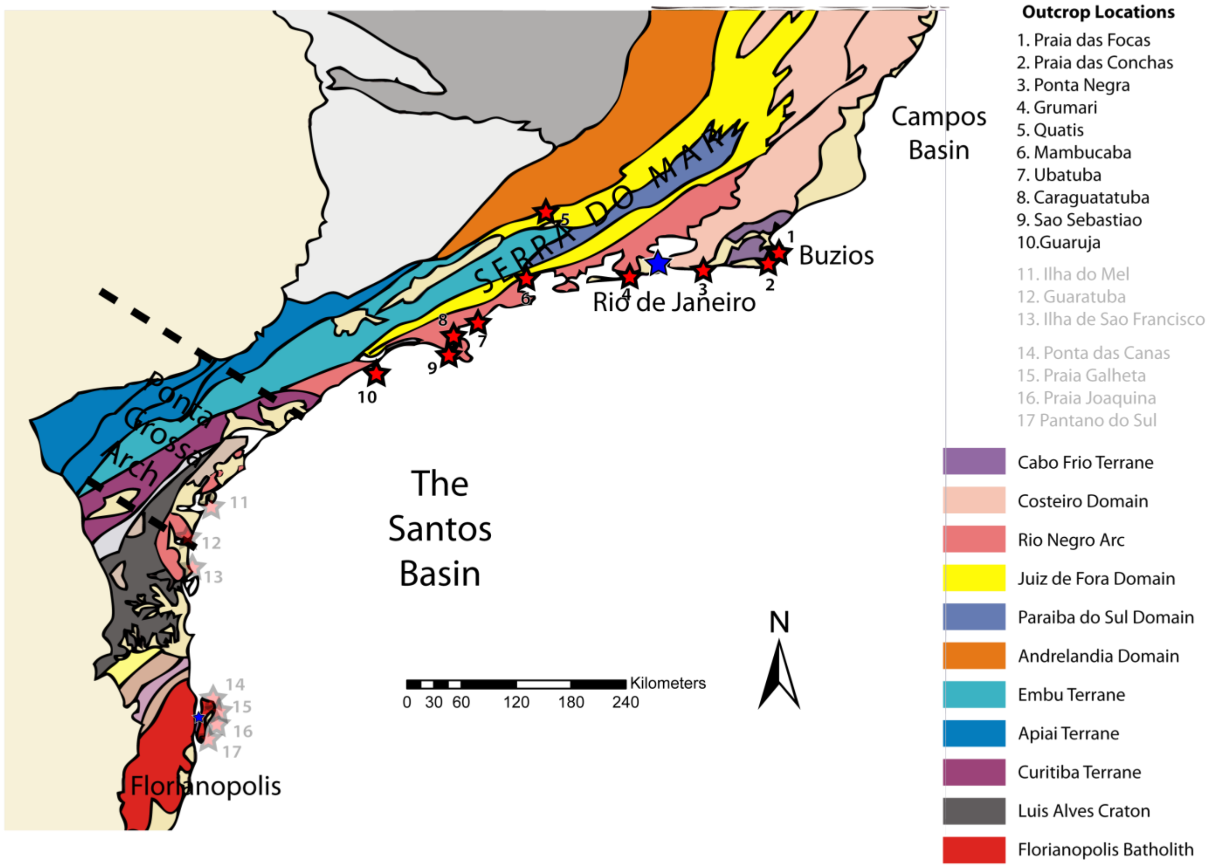


Figure 5.2 – Terrane map of the study area, after Passarelli et al. (2011), showing the locations of studied outcrops. Numbers 1-10 (highlighted) are the outcrops in the Serra do Mar domain, and are situated in the Rio Negro Arc, the Costeiro domain, the Juiz de Fora Domain, and the Cabo Frio Terrane in the North of the onshore study area.

5.4.1.1 Praia das Focas, Buzios, Rio de Janeiro state (RJ)

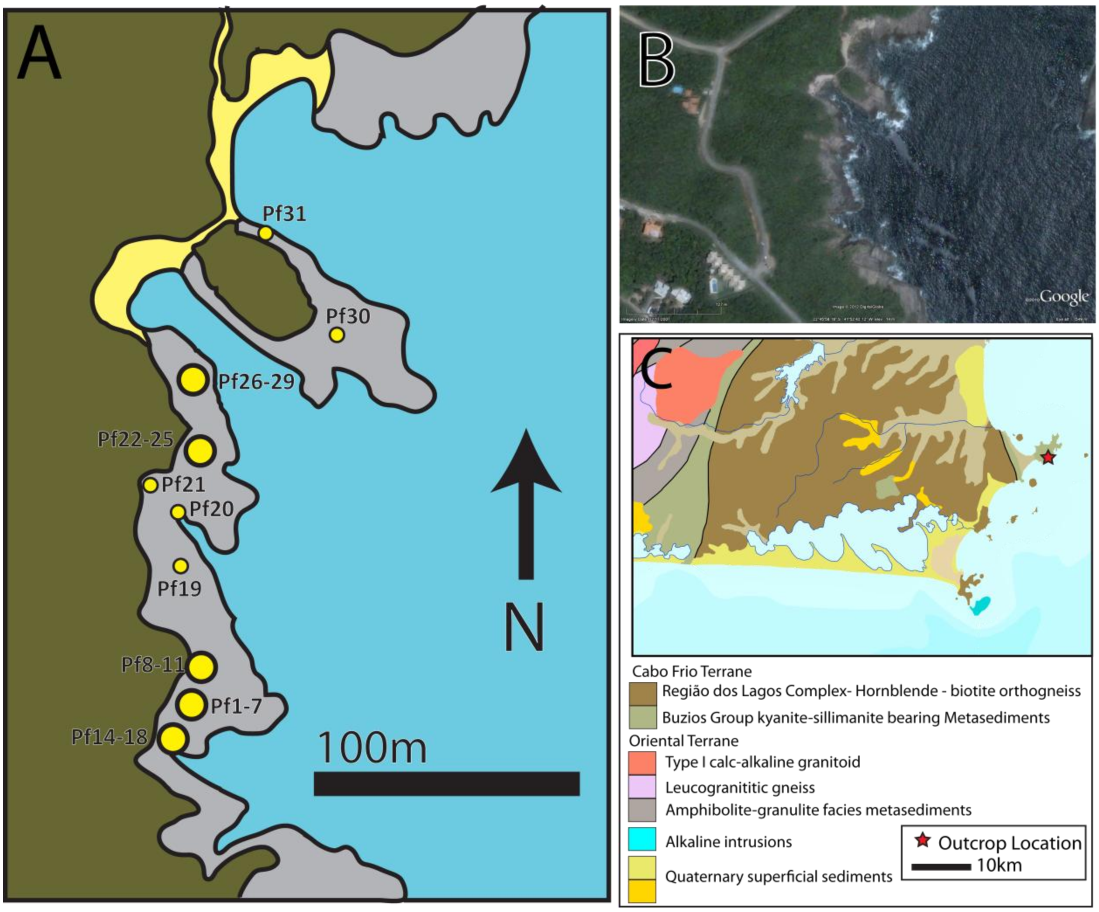


Figure 5.3. A. simplified map of the outcrop at Praia das Focas, showing the extent of exposure of basement rocks (grey), areas of vegetation (green), beaches (yellow), sea (blue) and waypoints at which data was collected (yellow circles B. Google earth aerial photograph of the outcrop C. geological map of the area, showing key basement lithologies and structures (black lines)

Outcrop Description

The basement at Praia das Focas consists of relatively shallowly dipping kyanite- and sillimanite-bearing metasedimentary rocks, although the Neoproterozoic Buzios group (chapter 2.3.1.1.11) displays a great deal of structural heterogeneity across the area. Fracturing and faulting appear to be intense, and a large fault can be observed at the southern end of the outcrop (Fig. 5.5a).

Outcrop-scale structures

Basement foliation at this outcrop is pronounced, with shallowly dipping amphibolite facies gneiss, showing dipping micaceous and more quartz-rich bands.

In map view, the outcrop is segmented by NW-SE trending faults, which appear to accommodate much of the deformation. These faults typically show dextral-normal oblique offsets (Figs 5.5b, 5.5c). Near to the main fault, complex networks of fluid-stained fractures were observed (Figs 5.4 a, b, c), possibly representing the damage zone of the main fault. Other faults with offsets of up to several centimetres were observed at this outcrop (Fig. 5.5a), and some faults show brecciation and cataclasis in the fault zone. Fault zones, where seen, range in width from a few centimetres to approximately 50cm for the large fault to the South of the outcrop . Fracturing around the main fault is intense, with many fractures demonstrating fluid staining, typically 5cm wide, and red in colour, on fracture surfaces and wall rocks (Fig. 5.4A). In addition to red staining, hard, fine grained black material can be observed within fractures and faults. The origin and composition of this material is unclear.

Among smaller fractures (those which do not display evidence for cataclasis or brecciation), little evidence for offset can be observed, and kinematic data is difficult to obtain (Fig. 5.4C). Cross cutting relationships between different brittle structures are not easy to interpret due to their low offsets of the smaller fractures, and the relatively large (10m) spacing between larger structures (Fig. 5.4B). However, the available evidence suggests that fractures appear to mutually cross-cut each other, with all sets observed to offset all other sets. These offsets appear inconsistent in terms of both sense and amount along the length of fractures.

A poorly exposed dyke was observed in this outcrop, its relationship with either basement fabrics or brittle structures cannot be established, as its margins cannot be observed.

A wide variety of fault and fracture orientations were observed, with three main sets of steeply dipping fractures trending N-S, NE-SW, and NW-SE (Fig. 5.6). The faults showing the highest amount of offset appear to show similar geometries to zero offset structures, including those without lineations. Where observed, lineations plunge shallowly, suggesting oblique or strike-slip offsets. On NW-SE faults, these lineations commonly plunge towards the southeast. NW-SE trending faults with dextral-oblique offsets make up a large number (approx. 60-80%) of the faults at this outcrop. No faults or fractures were observed dipping as shallowly as the basement foliation.

Interpretation

Praia das Focas is an excellent example of relatively high-offset normal and oblique-slip faults, apparently formed during the same deformation event. Faults here have been hypothesised as being related to the development of the Barra do São-João Graben to the north of Buzios (Mohriak and de Barros, 1990), based on the orientation of structures offshore. No evidence can be observed at this outcrop for the basement having controlled the geometry of the larger structures, although smaller-scale fractures and joints are restricted to less micaceous bands in the rock, possibly because this small scale deformation is accommodated by slip along foliation in the more mica-rich layers. Multiple sets of fractures observed at this outcrop could be interpreted as being typical of oblique, polymodal faulting, although they may have formed at different times. Inconsistent offsets along fractures and faults observed at this outcrop suggests either contemporaneous formation of fractures in multiple orientations, or complex cross-cutting relationships, due to later fractures reactivating older ones as they deform.

This outcrop shows that even where basement is very heterogeneous – in this case strongly foliated metasediments, the fabric anisotropy has only a small effect on the development of brittle structures if it is not preferentially oriented for slip. In this case, a few joints are restricted to the more quartz rich layers, but reactivation of basement fabrics by larger faults and fractures is not observed. In summary, the brittle deformation at this outcrop is seemingly not strongly influenced by the basement simply because these fabrics dip too shallowly to be reactivated during extension.

Field Photos and descriptions

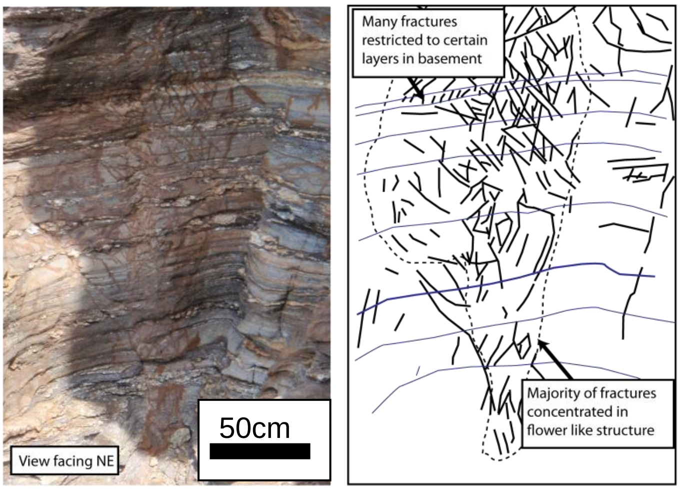


Figure5.4a. A branching network of Fe-stained fractures at Praia das Focas, cutting horizontal foliation. None of these fractures show any sense of offset. Many fractures are confined to more quartz rich layers, suggesting a local control on their development, possibly related to differences in mechanical strength between different layers.

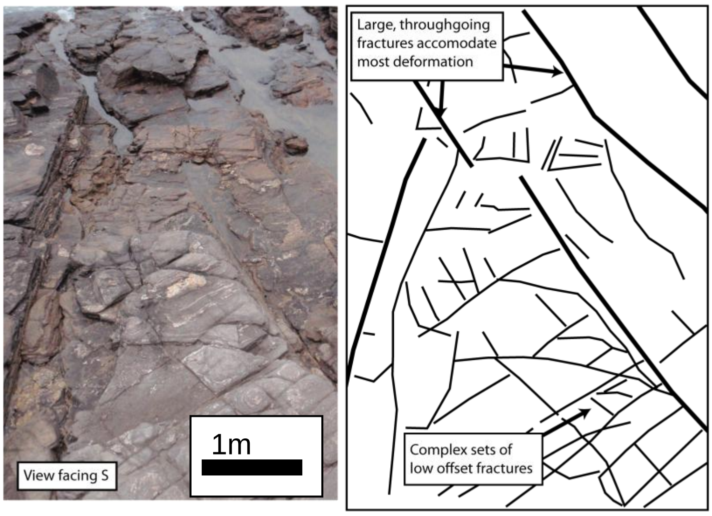


Figure5.4b. Multiple fracture sets exposed on the wave-cut platform at Praia das Focas show larger, throughgoing NW-SE fractures, with smaller fractures between them. Many of these fractures may be joints, formed either during tectonics or uplift. Identification of offset is impossible, though some of these fractures do show slickenlines.

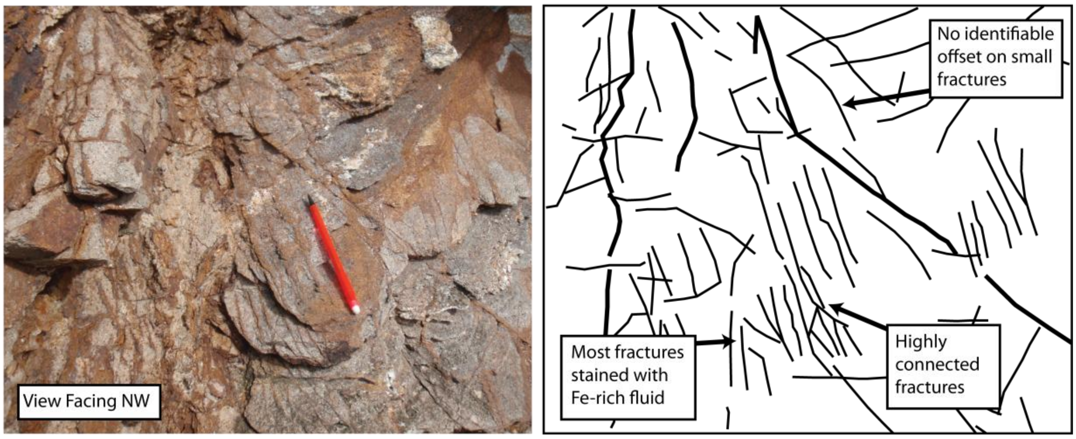


Figure 5.4c. The highest density of fracturing occurs closest to the major fault at Praia das Focas. These fractures are stained with red fluid, and show complex geometries typical of a fault damage zone. Cross-cutting relationships on these fractures, and others at this outcrop are very ambiguous, due to their low (or zero) offsets.

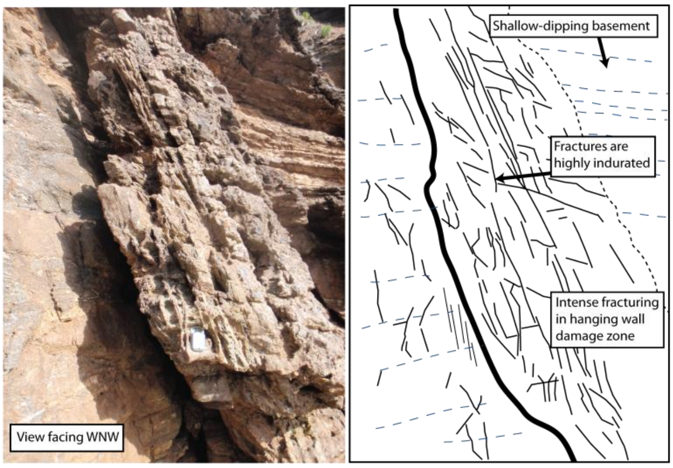


Figure5.5a. The large fault at the southeast of Praia de Focas outcrop, cutting shallowly dipping basement foliation. The fault and fractures are highly indurated with silica rich material. Complex fracture networks in the hanging wall contrast with relatively little fracturing in the footwall. Oblique slip slickensides suggest dextral-normal kinematics. Compass for scale in bottom-centre of image.

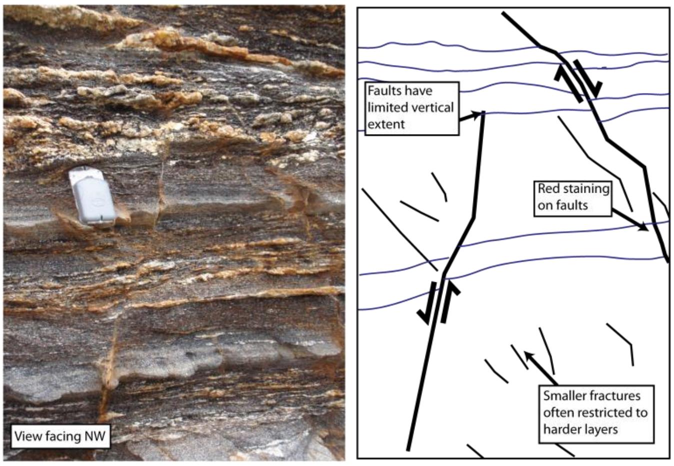


Figure5.5b. Small, normal offset faults exposed in a cliff at Praia das Focas, where identification of oblique offset is difficult. Faults do not extend far vertically, and tend to be limited to the more quartz-rich layers. Red staining is common on many structures, in particular those close to the large fault.

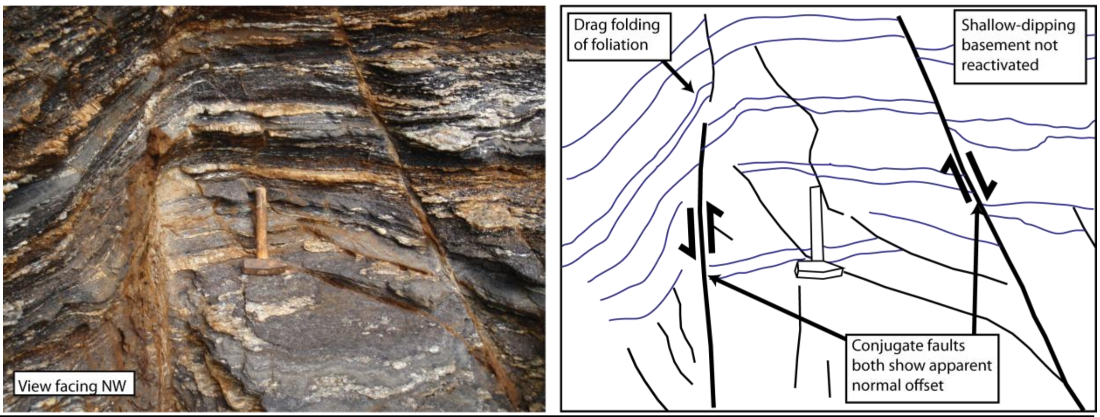


Figure5.5c. Two conjugate normal faults forming a horst. These faults have relatively large offset, up to 10's of cm, and do not appear to be affected by local foliation. Drag folding of the basement can be seen here, giving a normal offset shear sense. Red staining is confined to the faults and suggests fluid circulation during or after deformation. Red staining such as this is common at Praia das Focas.

Stereonet Data and description

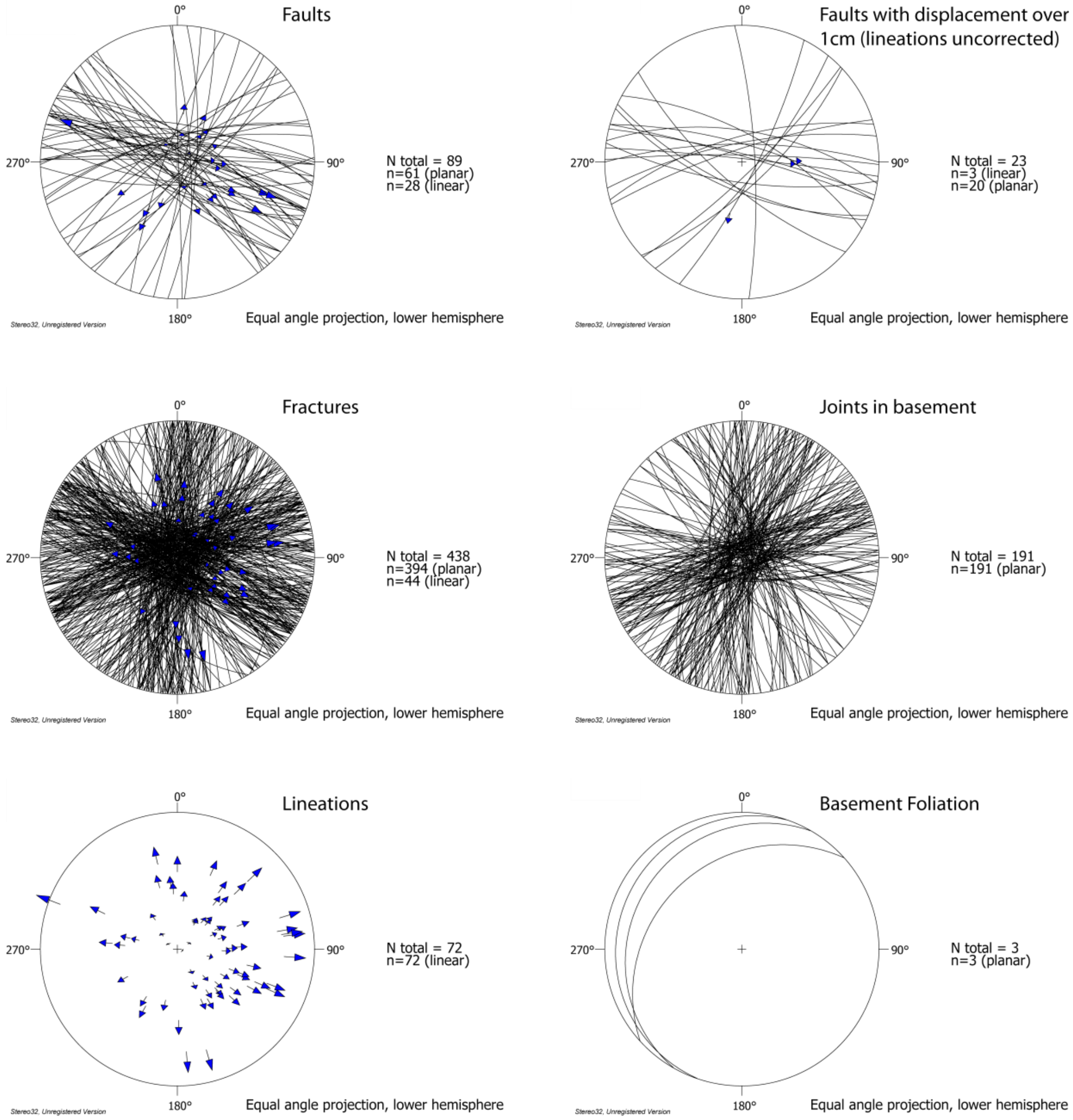
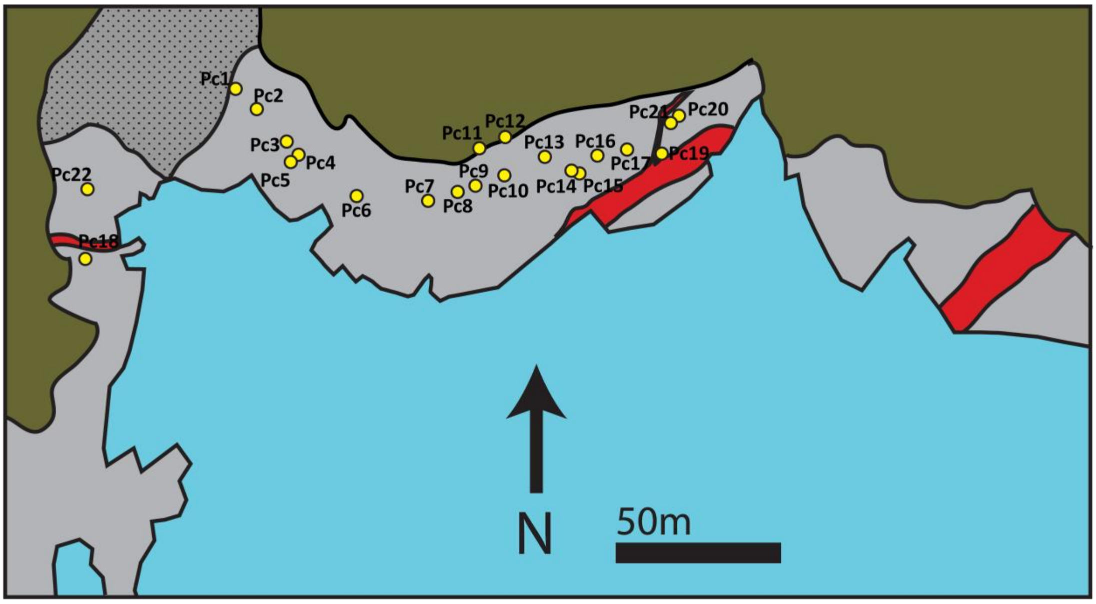


Figure5.6 Equal angle stereonets, plotted as planes (black lines) and lineation (blue arrows), for structural data collected at Praia das Focas.

5.4.1.2 Praia das Conchas, Cabo Frio, RJ



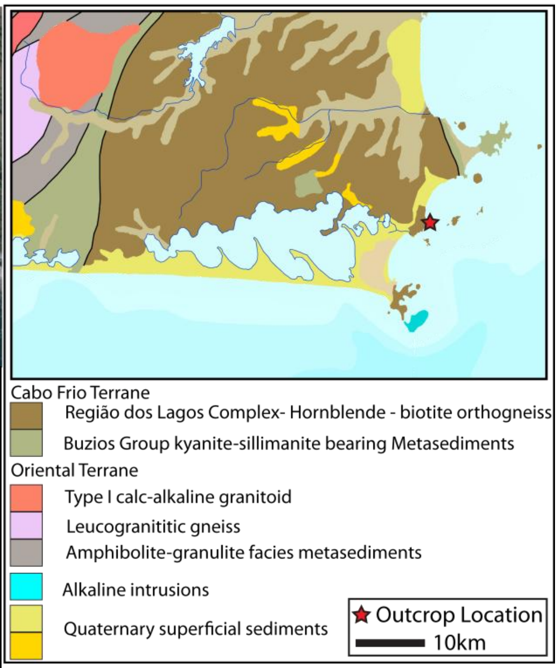


Figure 5.7A:Simplified outcrop map of Praia das Conchas, showing vegetated areas (green), key geological units (Basement - Grey, and Dykes - Red),and waypoints where data was collected; B: **Google Earth** image of the outcrop; C: Geological map of the local area, showing the extent of the Cabo Frio terrane and the basement rocks of the Regiao dos Lagos complex in which the outcrop is situated.

Outcrop Description

This is a large outcrop located on either side of a small rocky bay (Fig. 5.7). Cliffs to the west offer 3-dimensional exposure, while the eastern side of the bay comprises a series of flat platforms which are exposed to waves at high tide. This outcrop is formed of the orthogneisses of the Regiao dos Lagos Complex, which represents the Paleoproterozoic basement rocks of the Cabo Frio terrane (Chapter 2.3.1.1.11).

Outcrop-scale Structures

Basement fabrics at Prais das Conchas typically trend NW-SE, and dip steeply. Within the basement, a large (10m wide), N-S trending Brasiliano age dextral shear zone can be observed. Outside of the shear zone, basement fabrics are cut by numerous quartz veins and pegmatites.

The largest structure that can be observed at this outcrop is a NE-SW trending, 3-4m wide dolerite dyke. The dyke appears to have opened orthogonally, as pegmatites in the basement can be traced across it, perpendicular to its margins. The dyke margins can be observed to change direction (Fig. 5.8a) and branch in a number of places (Fig. 5.8b). A small number of lineations can be observed on the dyke margins, and are shown on Figure 5.11.

A large number of faults and fractures can be observed at this outcrop, falling into 3 main sets, based on their geometry. Faults typically show offsets between 1mm and approximately 10-20cm, and a number show good evidence for sinistral shear, either from lineations on the fault surface, or from direct observations of offset structures such as pegmatites and mineral veins (Fig. 5.10b). Many show evidence for cataclasis, with fine grained, pale coloured (or often red stained) fault rock found, with widths of 0.5-3mm along the fault plane. A number of faults and fractures also show evidence for fluid flow, with red-coloured staining common. I interpret this staining as formed from circulation of Fe- rich fluids, either during or after deformation, Where exposed in 3 dimensions, several NE-SW fractures show strike-slip offsets when viewed on a horizontal surface (Fig. 5.10b), and a normal offset when viewed in cliff sections. This, together with slickenlines plunging at between approximately 20 and 40 degrees demonstrates the oblique kinematics of faults at this outcrop.

The vast majority of faults, including those with large (1-30cm) offsets, trend NE-SW, with shallowly plunging lineations suggesting sinistral-oblique offset, typical of structures across the Ribeira belt. Fractures show more complexity with a NE-SW set, an NNW-SSE set and a NNE-SSW set (Fig. 5.11). The NE-SW and NNE-SSW sets are also reflected in the orientation of the dyke margins, highlighting the geometric link between the different structures, and suggesting that the dyke intruded along pre-existing fractures. The dyke and a large number of fractures cut this shear zone. A few fractures can be observed parallel to basement fabrics along the shear zone, but the majority of larger offset faults at this outcrop do not occur parallel to, or near the shear zone.

Interpretation

The basement fabric at this outcrop appears to have little influence on the development of later structures. There is also little evidence that the shear zone has affected the development of either the dyke, or the fractures and faults, either in term of location or orientation (Fig. 5.8c). The dyke cuts across the shear zone, and runs parallel to many of the brittle structures observed at this outcrop. The similarity between the orientation of the dyke margins and faults and fractures at the outcrop is good evidence that the dyke has intruded along pre-existing brittle structures (Figs 5.8a, 5.9a and 5.9c). Although the dyke itself appears to have opened orthogonally, the presence of jogs and branches in the dyke margins is consistent with the Pollard (1987) model for igneous intrusions under strike-slip shear stresses (see chapter 3, Fig. 3.27), suggesting that this dyke may have intruded into an obliquely deforming area.

Neither the density or the orientation of fractures at this outcrop change with proximity to the dyke, possibly suggesting that its intrusion was not accompanied by a major fracturing event. Some of the NNE-SSW trending faults and fractures crosscut the dyke, showing that they formed after its intrusion and cooling (Fig. 5.8b). The faults show mineralization (interpreted as calcite) along the fault plane, and show lineations plunging between 40 and 70 degrees, suggesting oblique offset. No structures with other orientations appear to cut the dyke. The fact that the only structures observed cutting the dykes trend NNE-SSW suggests a reorientation of brittle structures following the intrusion of the dyke, and that NNE-SSW faults formed later than both the dyke, and the NE-SW faults. Lineations observed on the dyke margins may have been formed due to magmatic processes, such as flow channelling as the dykes intruded (e.g. Baer and Reches, 1987), or by reactivation of the dyke margin.

At a number of localities within this outcrop, multiple sets of mutually cross-cutting fractures can be observed, suggesting these may be polymodal faults. The three main sets of faults at this outcrop would suggest that this faulting is 'trimodal' (e.g. Reches, 1978). Polymodal faulting is typical of regions which have deformed by oblique extension/transtension (see chapter 3.2).

Field Photos and descriptions

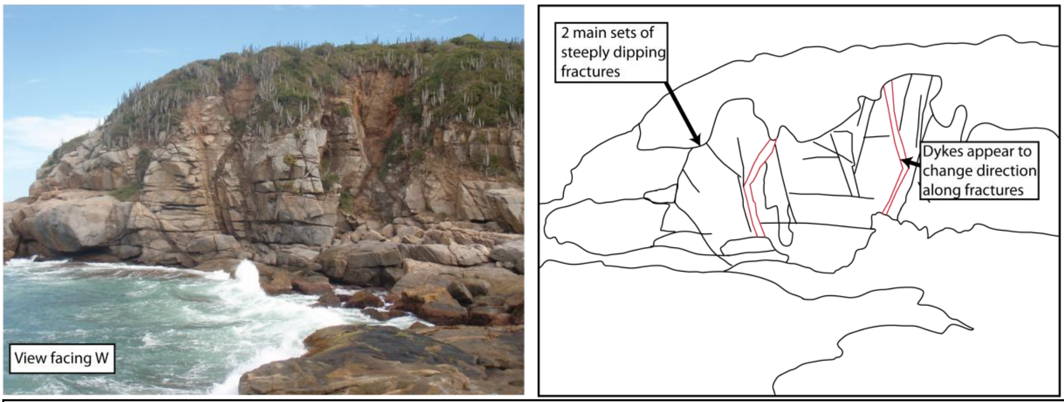


Figure 5.8A.Dykes seen in a cliff section at Praia das Conchas (locality Pc18). The dykes clearly follow the two main sets of fractures seen here (NW-dipping and SE-dipping), although they do not appear to be affected by shallowly dipping structures. These dykes are interpreted as having intruded along pre-existing fractures, as it is the simplest explanation for the close similarity in their geometries. Cliff is ~ 20m high

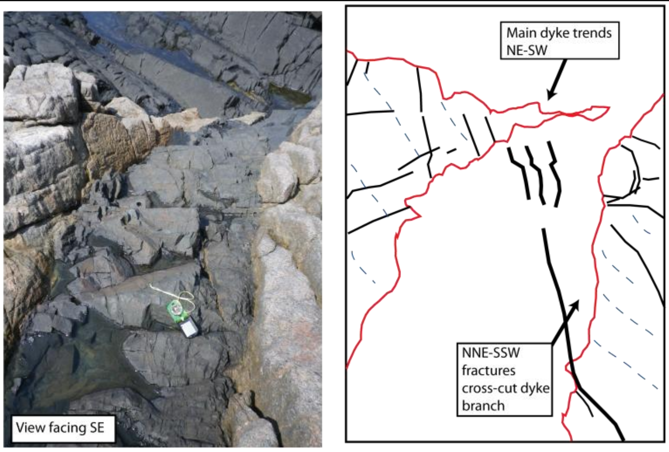


Figure 5.8b. This smaller dyke branches from the largest dyke seen at Praia das Conchas. The Smaller Dyke is cut by NNE-SSW trending fractures, some of which have quartz mineralization along the fracture surface.

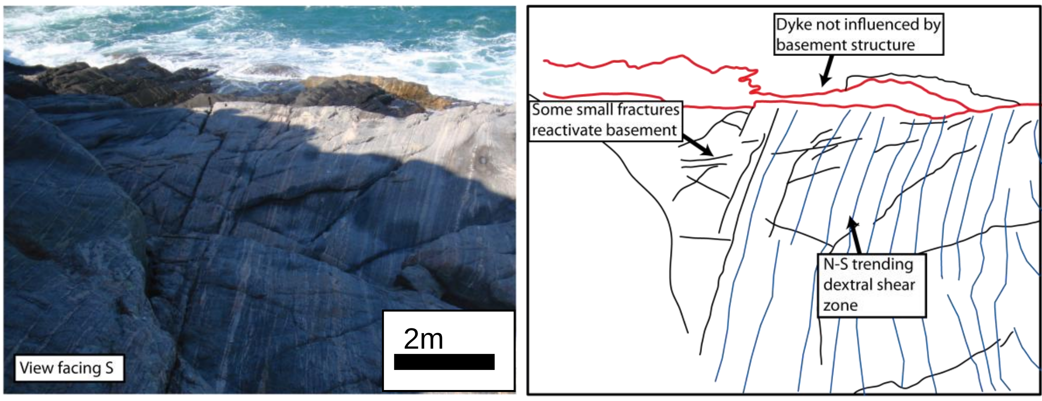


Figure 5.8C A N-S trending basement shear zone is seen at Praia das Conchas, cut by the large dyke. This relatively large basement structure has no control on the geometry of the dyke, although it does appear to have been reactivated by a small number of open fractures. Many other fractures simply cross-cut the shear zone. Most fractures do not cut the dyke, but a number of NNE-SSW tending fractures do (Fig. 5.8B).

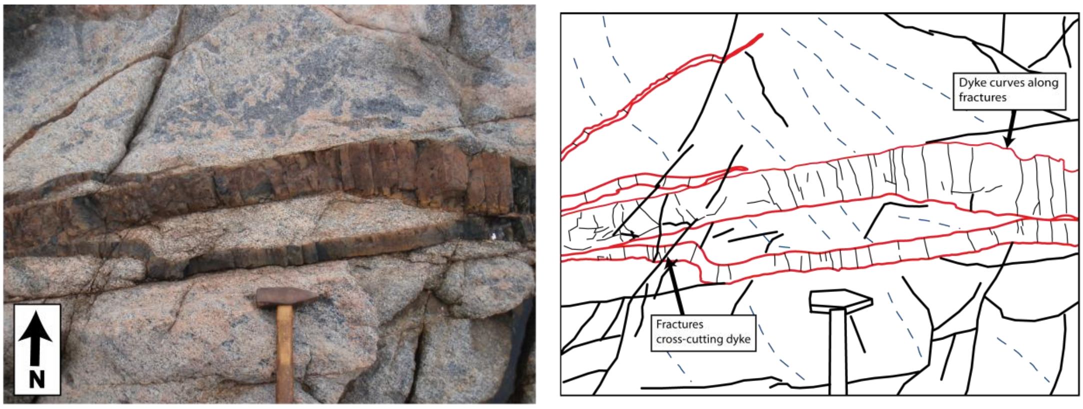


Figure 5.9A.A small dyke branching around a block of basement gneiss at Praia das Conchas. The dyke clearly follows fractures in the basement, branching between two NE-SW trending fractures. NNE-SSW fractures later crosscut the dyke. The dyke and fractures clearly crosscut the NNW-SSE trending basement,

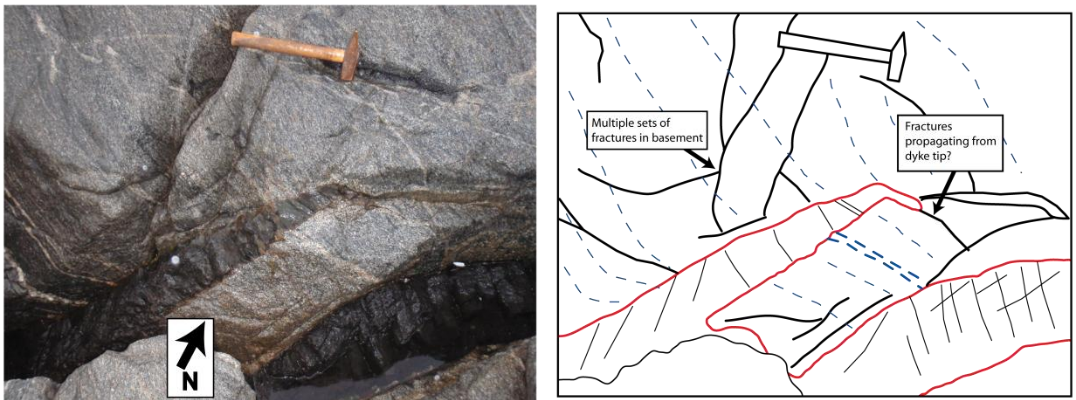


Figure 5.9B. A broken bridge structure along a smaller dyke at Praia das Conchas. This segmentation of the dyke could be interpreted as intrusion under shear stress (see chapter 3). Complex fracturing in the basement does not appear to crosscut the dyke, and the dyke again intrudes parallel to some of the basement fractures (bottom right of the image).

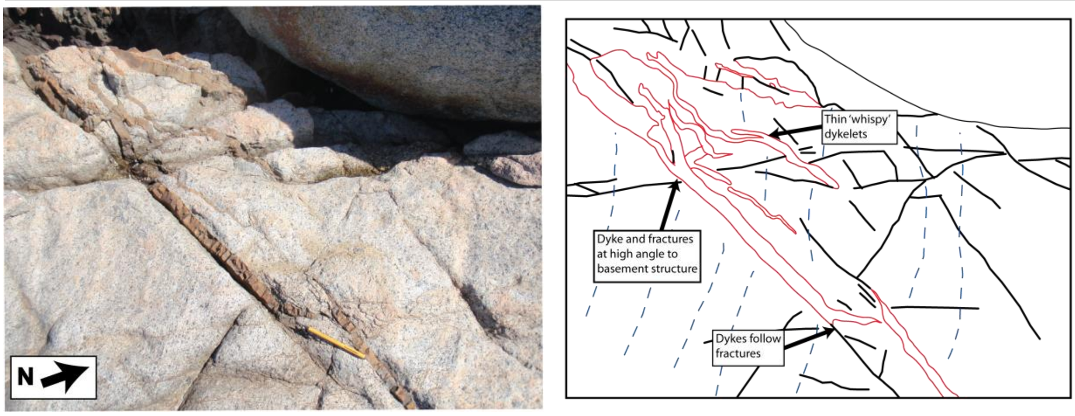


Figure 5.9C. Smaller dykes seen at Praia das Conchas. While the larger of the small dykes in this image trends closely parallel to brittle fractures, there is a significant population of smaller dykes and dyke branches that show a more chaotic geometry,

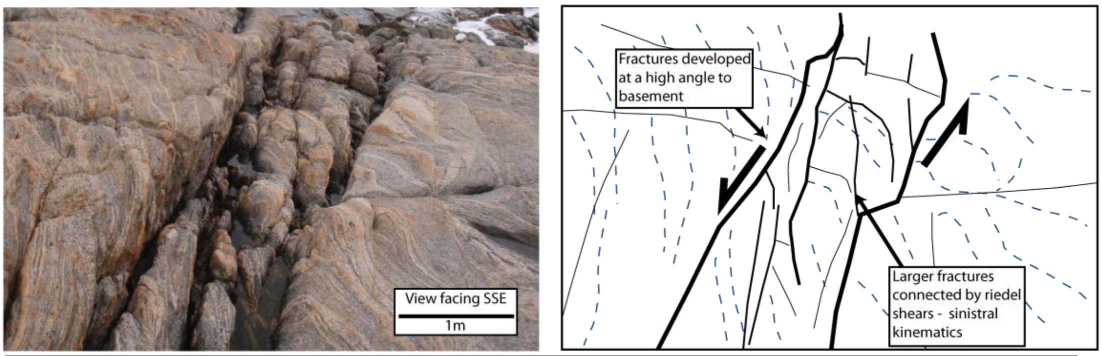


Figure 5.10A. Riedel shear like structures are observed linking two longer, thoroughgoing structures. Interpreting these as such suggests this NNE-SSE trending structure has a sinistral offset. Away from the structure, fractures are discrete and widely spaced. Almost no fractures appear to reactivate the strong ductile foliation at Praia das Conchas.

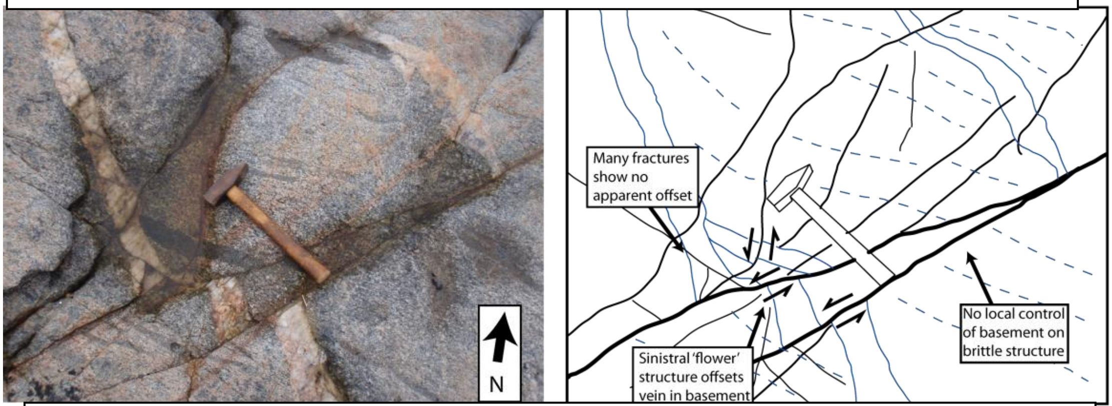


Figure 5.10B. Sinistral faults at Praia das Conchas can clearly be identified crosscutting basement veins. These branching faults appear to form a flower structures (see chapter 3), and are typical of oblique- or strike-slip deformation. Other structures in this image, although parallel and sub-parallel to the relatively high offset faults, show little or no offset.

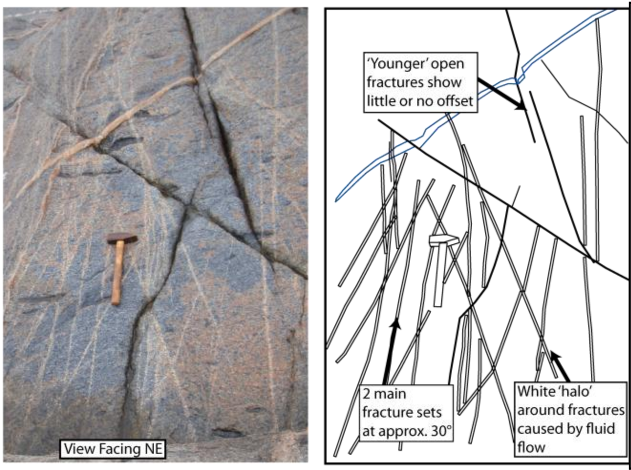
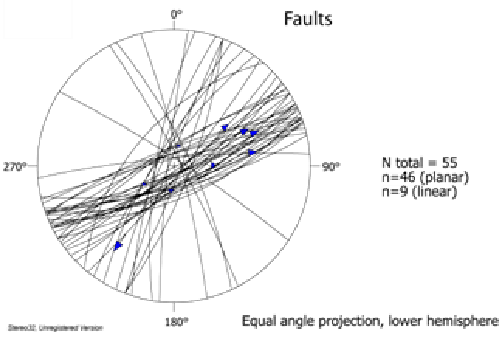
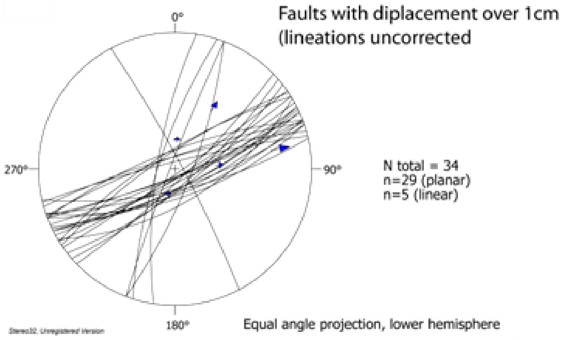
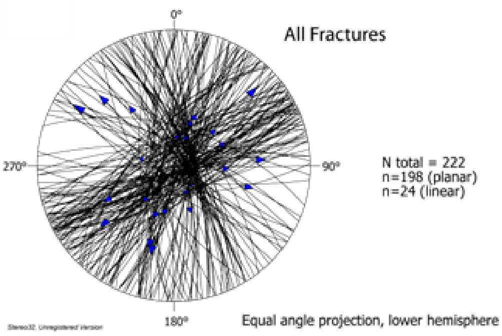


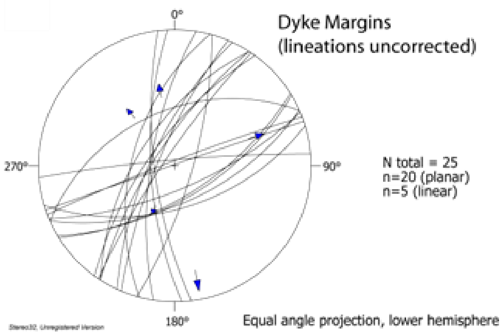
Figure 5.10C. Sets of pale stained fractures, cutting basement structure at Praia das Conchas. These fractures show no sense of offset, and due to their similar staining and small fills of cataclasite these fractures are contemporaneous with one another.. This geometry is consistent with non-andersonian oblique tectonics. Younger open fractures appear to cross-cut these.

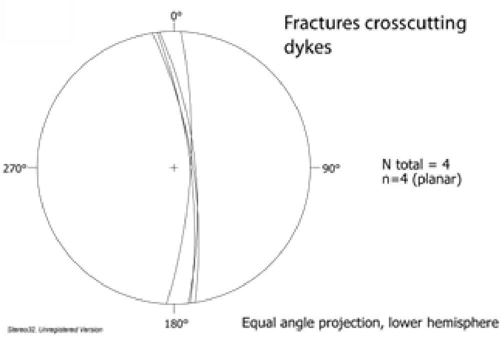
Stereonet Data and description

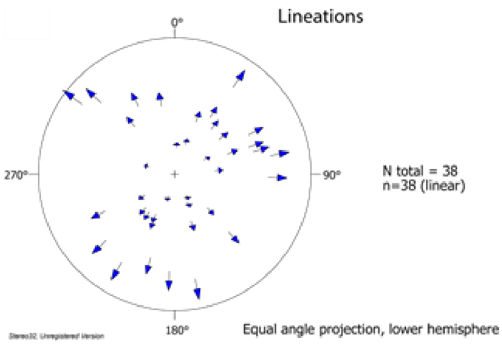












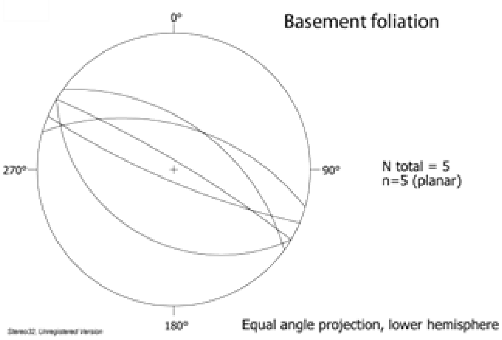


Figure 5.11. Equal angle stereonets of structural data from Praia das Conchas, showing planes (black lines) and lineations (blue arrows).

5.4.1.3 Ponta Negra, RJ

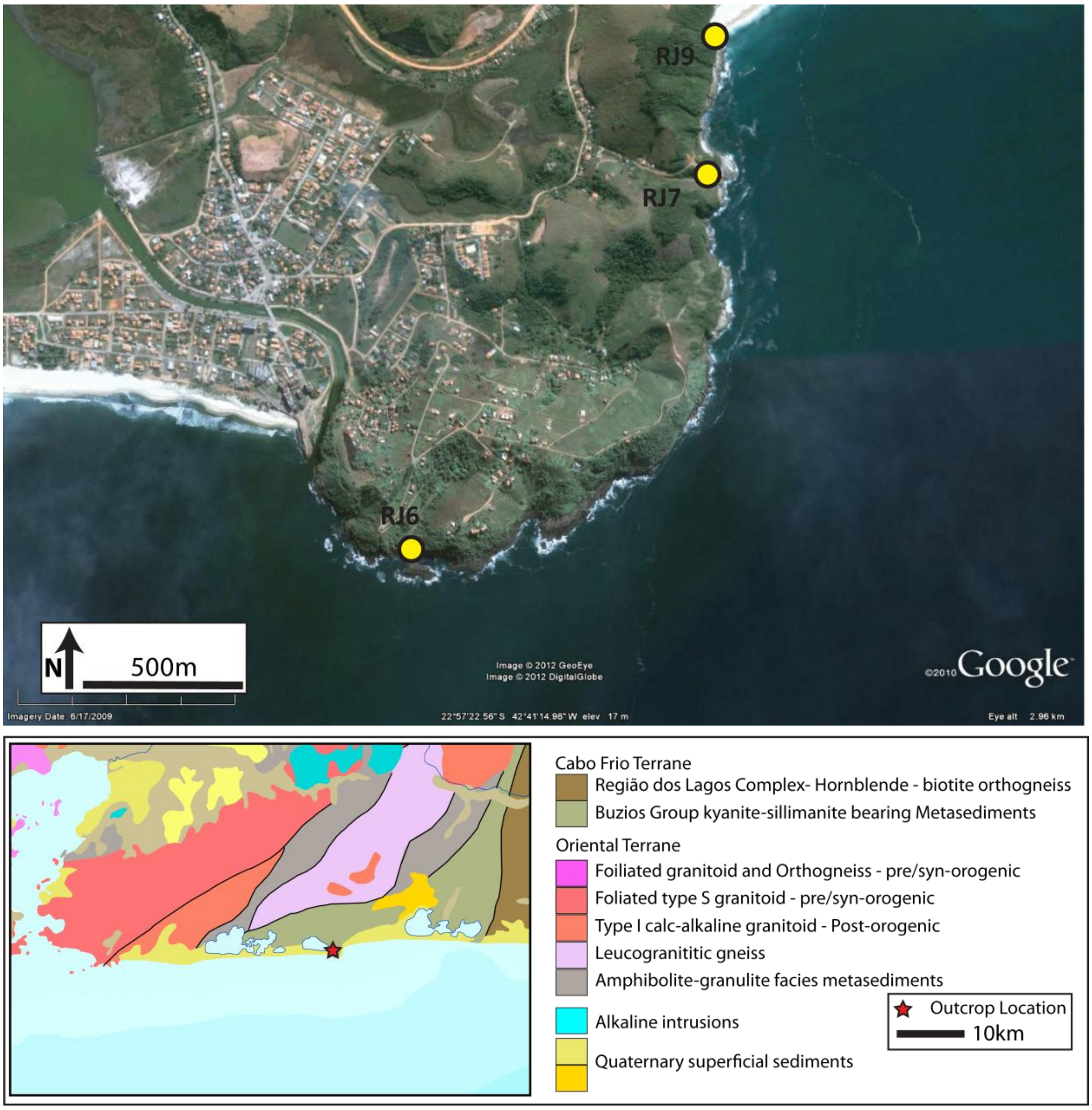


Figure5.12A. Google earth aerial photograph of the outcrop region at Ponta Negra, showing the locations of outcrops visited (yellow circles). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

This outcrop is found near to the western limit of the Cabo Frio terrane (Chapter 2.3.1.1.11), and is also the location of the contact between the high grade gneissose basement of the Paleoproterozoic Regiao Dos Lagos complex and the metasediments of the Neoproterozic Buzios group (chapter 2.3.1.1.11). Two small exposures were studied in the Ponta Negra area. The first (Rj6 on Figure 5.12A) consists of low-lying, boulder-strewn rocky shoreline, while the second (Rj7 on Figure 5.12A) is found to the east of a small beach, at the base of a steep grassy slope.

Outcrop-scale structures

Basement foliation is variable across the outcrop, with steeply-dipping foliation with both SW and NE dips. The composition of basement ranges from the metapelites of the Buzios group (similar to those seen in Praia das Focas – 5.4.1.2), to the quartzofeldspathic orthogneisses of the Regiao dos Lagos complex (also seen at Praia das Conchas).

The majority of brittle structures at this outcrop consist of fractures with little to no offset, although some faults were also observed. Faults trend NE-SW, with both shallowly-plunging and steeply-plunging slickenline lineations observed. Fractures display a much wider array of orientations (Fig. 5.14), with basement-parallel and -oblique fractures in different basement lithologies, with metasedimentary basement typically showing basement-parallel fractures.. Due to the relatively low amounts of offset (fewer than 0.5cm, where observed) on most of these fractures, cross-cutting relationships are difficult to identify. However, a potential 2m offset of a NE-SW structure was identified, along a basement-parallel fault (Fig. 5.13A). A 5-8m wide, NE-SW-trending dolerite dyke is observed to have intruded the Regiao Dos Lagos complex to the east of this outcrop. NE-SW trending dextral offset faults, containing <2mm thick fine-grained green/brown cataclasite (Fig. 5.13C), can be observed trending parallel to the dyke. Figure 5.14 shows structural data collected at this outcrop.

Interpretation

Some fractures trend parallel to basement fabrics, and therefore appear to be influenced by the orientation of the metasedimentary basement fabric (Fig. 5.13B), possibly due to the strong foliation and compositional heterogeneity of the metasediments compared with higher grade (amphibolite to granulite facies) material in this and other terranes. The basement fabric-parallel fault which crosscuts an earlier fracture highlights the fact that the age of basement-influenced deformation is uncertain, and may have taken place some time after rifting. The multiple orientations of slickenlines seen on different faults suggest a variation in kinematics, possibly as a result of reactivation. Deformation near to and parallel to the dyke is more likely to be rift-related, although it is impossible to date these structures relative to the dyke, because they cannot be observed either to cut the dyke, or be cut by it. The dextral offsets on the dyke-parallel faults are inconsistent with other NE-SW trending faults observed within the Serra do Mar region, where the majority of NE-SW trending faults display sinistral kinematics.

This outcrop highlights the role that steeply-dipping, strongly foliated basement can play in influencing the development of later structures. The dyke here trends roughly parallel to other dykes in the area, and its doleritic composition suggests it may be of a similar 135-125Ma age to the other rift-related dykes.

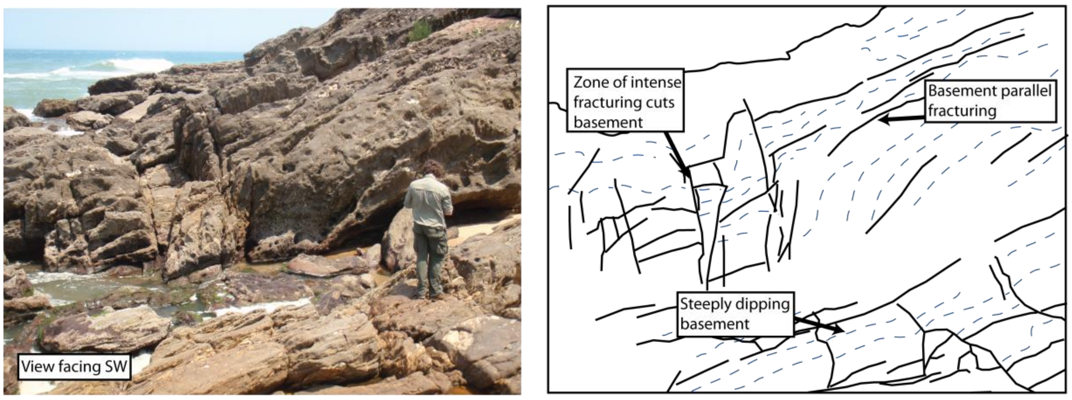


Figure 5.13A. An outcrop of metasedimentary rocks at locality RJ6. Basement dips steeply to the southwest, and is reactivated by NW-SE trending fractures. These fractures appear to be crosscut by NE-SW trending structures with possible sinistral kinematics (based on apparent Riedel shears).

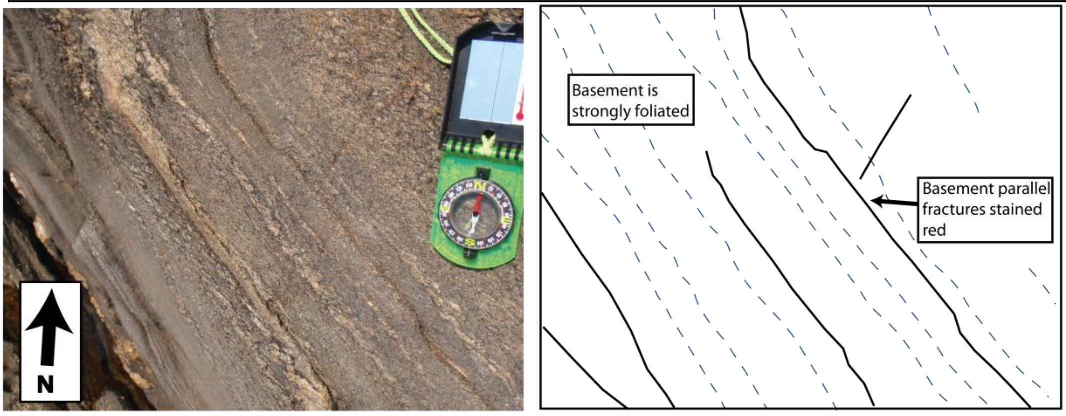


Figure 5.13B. Close-up of the basement parallel fracturing in the Metasediments at Ponta Negra. These fractures show red staining and minor red coloured fault rock. Offset amount is difficult to ascertain given the basement parallel nature of the fractures

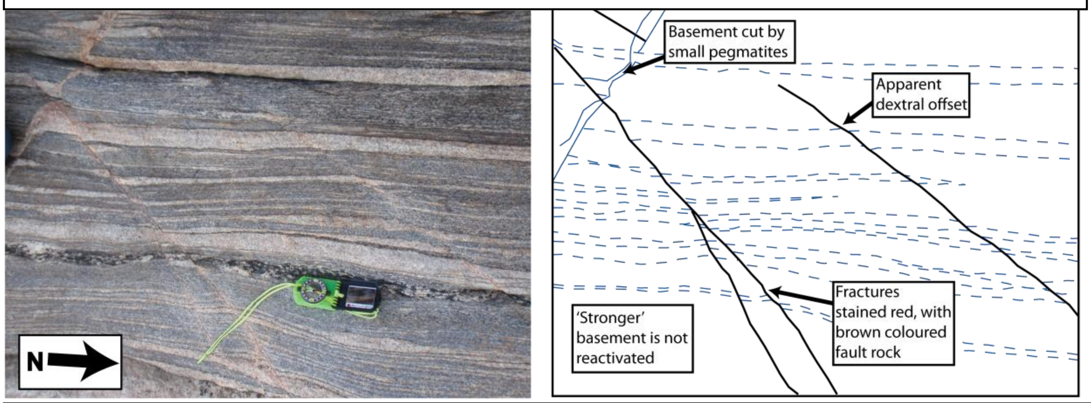


Figure 5.13C. The N-S gneissose basement of the Cabo Frio terrane is not reactivated at Ponta Negra. NE-SW trending apparent dextral offset faults cut the basement. These faults typically have pale coloured-red fault rock, and offsets less than 5cm

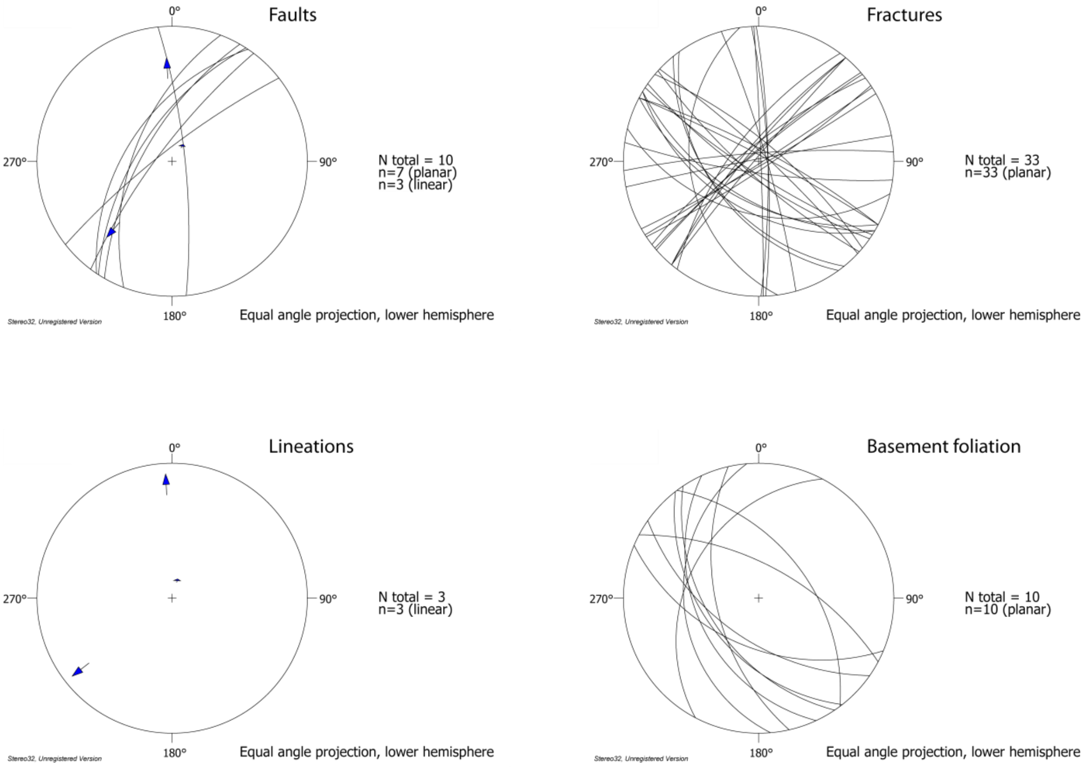


Figure 5.14 Stereonets of structural data collected from Ponta Negra. Equal Angle Projections. Planar structures are plotted as black lines, lineations as blue arrows.

5.4.1.4 Grumari, RJ

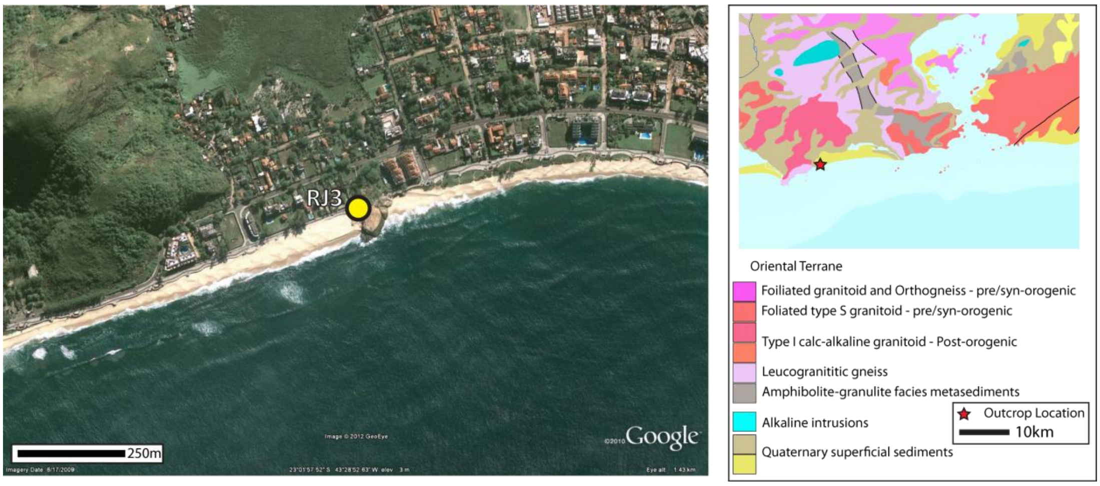


Figure 5.15 A. Google earth aerial photograph of the outcrop region around Grumari, showing the locations of outcrops visited (yellow circles). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop description

This is a small outcrop on the outskirts of Rio de Janeiro showing a narrow (50cm wide) dolerite dyke within Neoproterozoic granitoid basement of the Oriental Terrane (chapter 2.3.1.1.9) (Fig. 5.15A).

Outcrop Scale Structures

No foliation can be identified in the basement rocks at Grumari, The dolerite dyke observed at this outcrop is approximately 50cm wide, and displays right-stepping en-echelon segments, and broken bridges along its length (Fig. 5.16A). The dyke trends WNW-SSE, and many dyke-parallel fractures can be observed. 4 small faults, with slickenline lineations but no observable offsets, trending NNW-SSE can be observed here, and one 50cm wide zone of fractures trending approximately N-S contains Riedel shear-type geometries, suggesting dextral offset (Fig. 5.16B). Fractures around the dyke show no evidence of any offset of basement structures. Figure 5.17 shows stereonets of structural data collected at this outcrop.

Interpretation

The dyke is doleritic in composition, is narrower than all of the other doleritic dykes seen in the Serra do Mar Domain, and does not trend parallel to other dykes in the region. En-echelon dyke segments and broken bridges suggest that the dyke intruded during oblique extension (see chapter 3.3.4.3), although its WNW-SSE trend is inconsistent with the rest of the dykes of the Serra Do Mar swarm. No basement reactivation is identified here, due to the lack of basement foliation. The difference in kinematics at this outcrop when compared with the more typical NE-SW trending dykes observed at other outcrops such as Mambucaba and Praia das Conchas (sections 5.4.1.2 and 5.4.1.5) could either reflect the complex strains associated with oblique extension (see chapter 3.3.4.3) or it could be due to different kinematics associated with a different extension event (see chapter 2.4 for discussion of rift-related and post-rift deformation in the area). A further possibility is that the different orientations of brittle structures seen at this outcrop could be due to the lack of pre-existing basement fabric, though the presence of NE-SW trending structures at other outcrops with no basement influence does not support this view.

Figure 5.16A. The dyke at Grumari, showing en-echelon geometry consistent with sinistral shear during emplacement. A broken bridge can be seen on the vertical section of the dyke and suggests a vertical element of dyke emplacement. Fractures here appear parallel to the dyke.

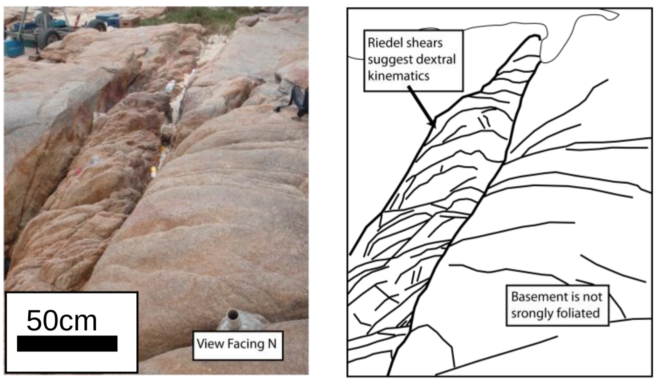


Figure 5.16B. The NNE-SSW trending fracture set with apparent dextral kinematics. Away from this larger structure and the dyke, relatively little fracturing can be seen, showing that deformation is highly localized to key regions. No basement reactivation is observed at Grumari.

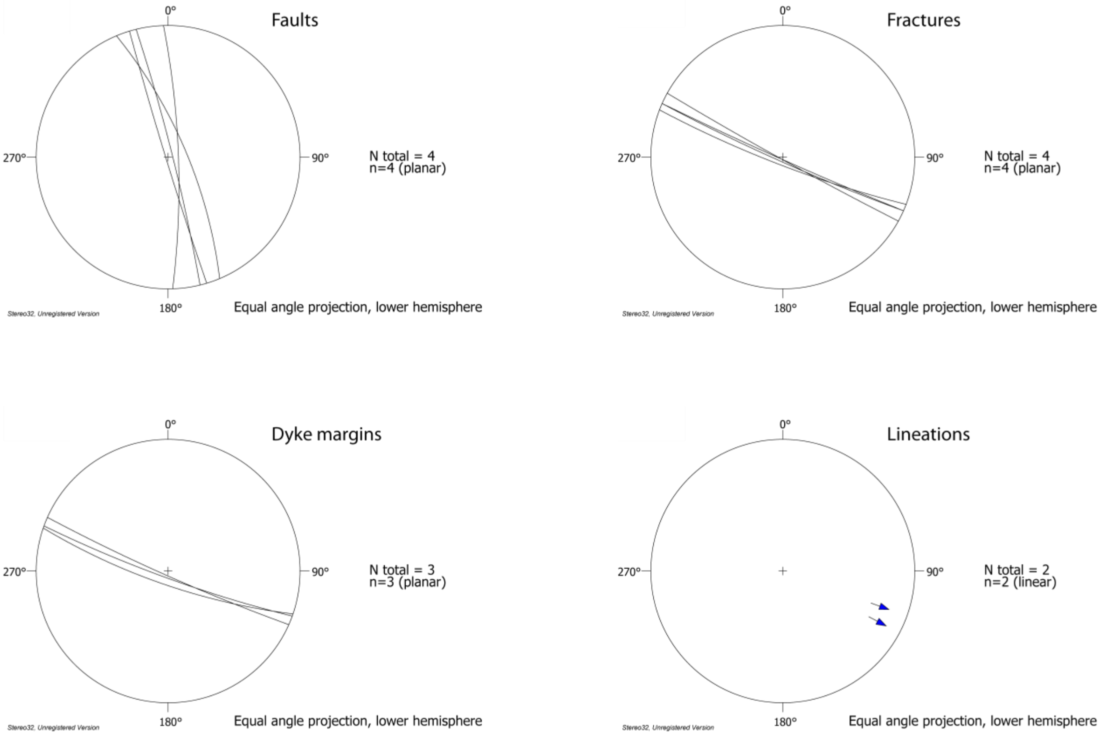


Figure 5.17 Stereonets of structural data collected from Grumari. Equal angle projections. Planar structures are plotted as black lines, and lineations as blue arrows.

5.4.1.5 Mambucaba, RJ

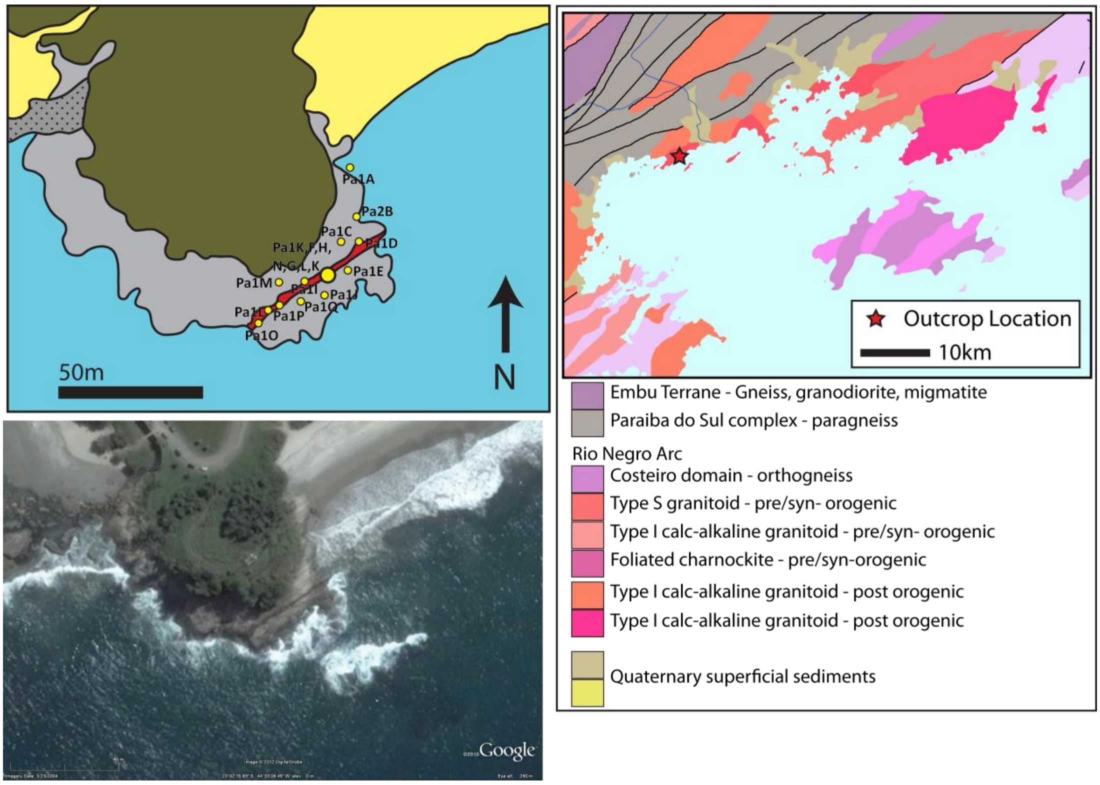


Figure 5.18 A. simplified map of the outcrop at Mambucaba showing waypoints visited. The dyke is highlighted in red, and basement in grey. The beach is yellow, the sea blue, and areas where exposure is absent due to vegetation are green B. Google earth aerial photograph of the outcrop region, showing the locations of outcrops visited (yellow circles). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop description

This outcrop is located at the western end of a long beach, and near to the mouth of the Mambucaba River (Fig. 5.18A). A 10m wide strip of rock exposed between the rainforest and the coast (Fig. 5.18B) shows a NE-SW trending, 125-130Ma (on the basis of composition) dolerite dyke intruded into NE-SW trending, steeply dipping Neoproterozoic gneissose basement of the Rio Negro arc (Chapter 2.3.1.1.10) (Fig. 5.18C). Many faults and fractures can be observed at this outcrop, and are described below.

Outcrop Scale Structures

Basement fabrics at Mambucaba trend NE-SW and dip steeply. Basement is strongly foliated between quartzofeldspathic, and much more micaceous bands. While some variation in strike is observed across the outcrop (Fig. 5.21). Foliation is relatively planar in the region of the dyke and fractures (described below).

Two dominant fault trends are observed, trending NNE-SSW and NW-SE. Of the larger offset (1-5cm) faults, the vast majority are from the NNE-SSW set. The trends of fractures are more widely distributed than the fault trends, also forming sets trending NNE-SSW and NW-SE, parallel to the faults, and a third set, trending NE-SW, parallel to basement foliation and the dyke margins (Fig. 5.21). Slickenline lineations are mostly moderately dipping. The dyke margins show a wide array of directions, with a number of jogs and offshoots seen (Fig. 5.20C) although the dominant dyke trend is NE-SW. Fractures crosscutting the dyke appear to have variable orientations. The dyke contacts appear to reactivate basement fabrics, particularly more micaceous bands within the gneiss. Brittle structures also appear to reactivate basement fabrics, although a large number also cross-cut basement fabrics (Figs 5.19 A, B, C, 5.20A). Faults show a variety of offset senses, with two sets of NE-SW structures showing sinistral and dextral kinematics (Fig. 5.19C). Larger basement fabric-parallel faults and fractures form geometries associated with sinistral strike-slip deformation, such as apparently dilational bends and en-echelon fractures (Fig. 5.19A). Cross-cutting relationships are ambiguous, with no set of fractures appearing to consistently cut older structures. Many faults and fractures trend parallel to basement fabrics, but dip in the opposite direction to the dip of the ductile foliation. A N-S trending array of right-stepping en-echelon fractures can be observed cutting the dyke (Fig. 5.20B).

Interpretation

The reactivation of basement fabrics by dyking, faulting and fracturing at this outcrop appears to be the result of the strongly heterogeneous basement. Micaceous bands are reactivated, whereas more quartzofeldspathic bands are not. Where basement structure is more complicated, or where no such micaceous horizons are present, basement fabrics do not seem to be reactivated, and there is a significant population of structures cross-cutting the basement, suggesting it is the relatively planar foliation of parts of this basement that make it ideal for reactivation.

It is unclear whether the dyke has intruded directly into basement, or if it has intruded into pre-existing fractures and faults which reactivate basement. The similarity in geometry between the dyke margins, fractures and faults suggests that the dyke intrudes along pre-existing fractures. The presence of en-echelon fractures within the dyke suggests a tectonic event postdating dyke intrusion. The presence of flower-type linked fault structures (Fig. 5.19C) highlights the oblique nature of the deformation in the Serra do Mar region. Regionally, this is one of the few outcrops studied where basement reactivation can be clearly identified.

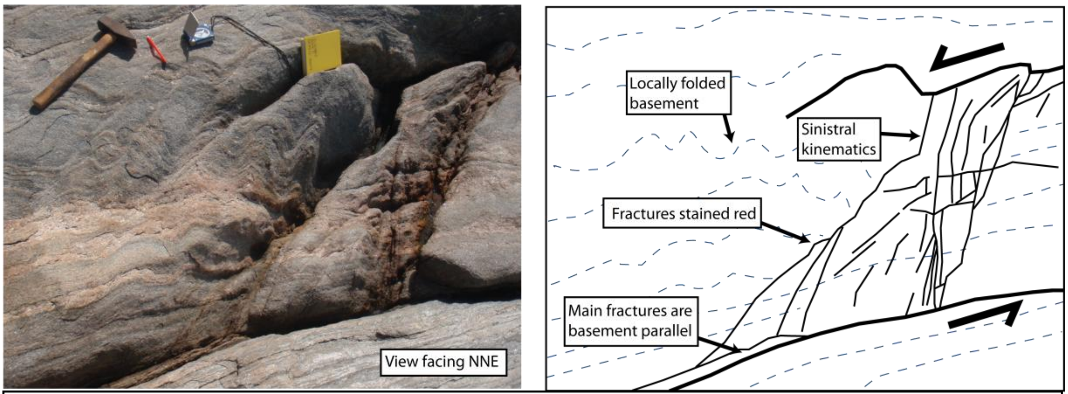


Figure 5.19A. A sinistral dilational step between two basement parallel fractures at Mambucaba. While it is difficult to make direct observation s of offset along these structures, due to their basement parallel nature, and low displacements, geometries such as these are useful in establishing kinematics. Red staining like this is typical of fractures across the region.

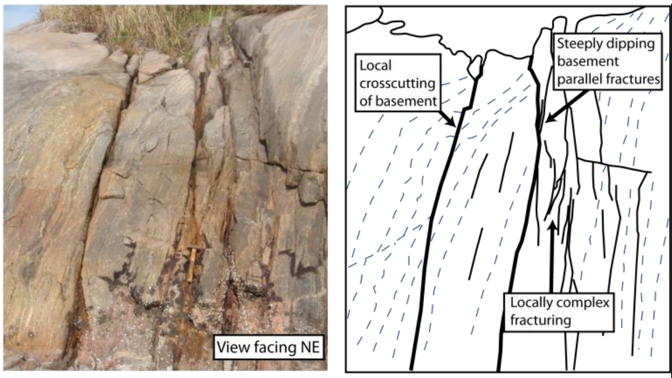


Figure 5.19B. Basement parallel fractures at Mambucaba. Steeply dipping, strongly heterogeneous basement such as this is ideal for reactivation. However, where the basement structure changes, fractures do not appear to change in orientation or structural style

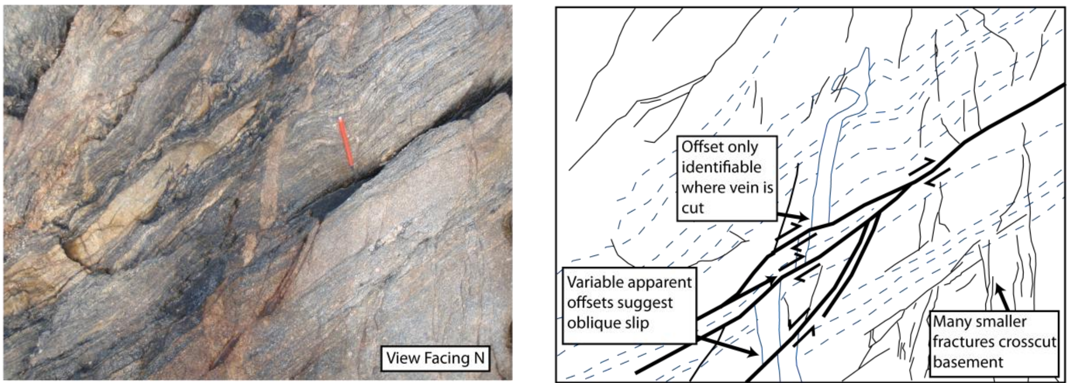


Figure 5.19C. A basement-parallel flower structure, with apparent sinistral and dextral offsets. These different apparent offsets suggest a dip-slip element to the deformation at Mambucaba. The dextral offsets are not typical for this orientation of structure in the region, and may either reflect local variation in stress orientations (partitioning), reactivation, or a non rift-related event.

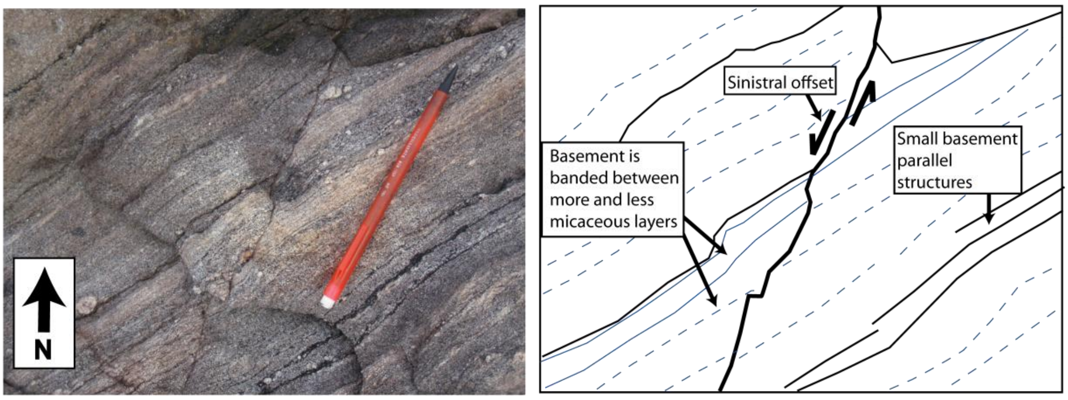


Figure 5.20A. A NNE-SSW sinistral fault crosscutting basement at Mambucaba. Smaller basement parallel fractures are also present, in more micaceous (darker in this image) layers within the basement. The NNE-SSW sinistral structures contrast with the more NE-SW dextral flower structure seen in figure 5C

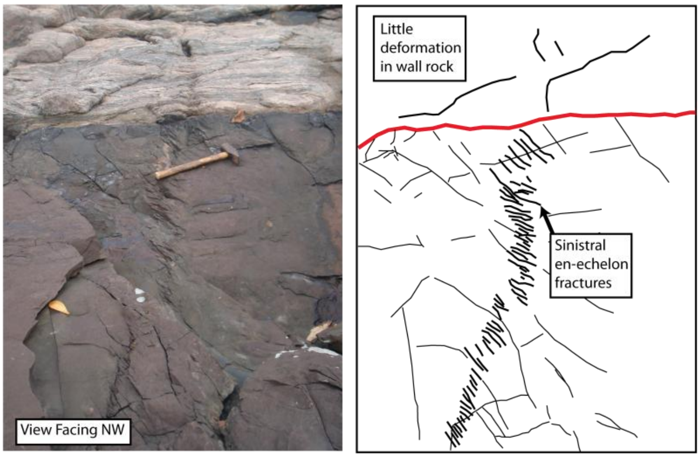


Figure 5.20B. Roughly N_S trending network of en-echelon fractures cutting the dyke at Mambucaba. These fractures represent incipient deformation within the dyke after its formation, which did not progress into the basement in this orientation, possibly due to the mechanical difference between the two units.

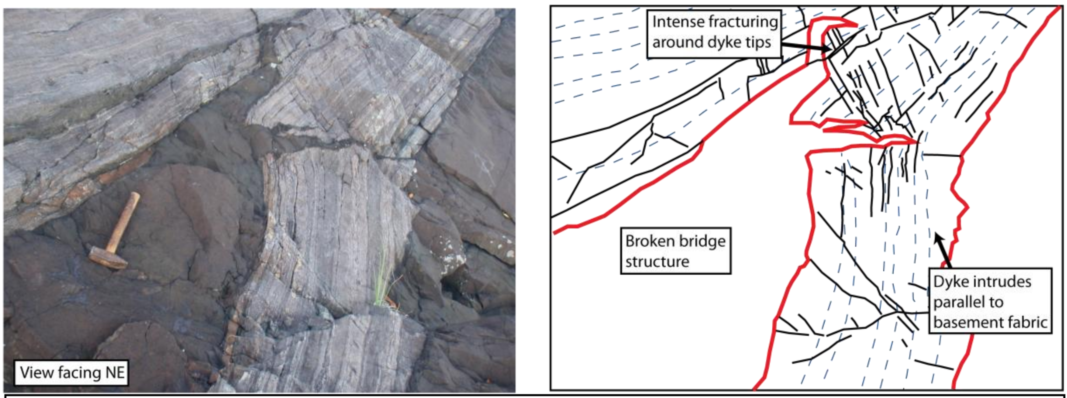
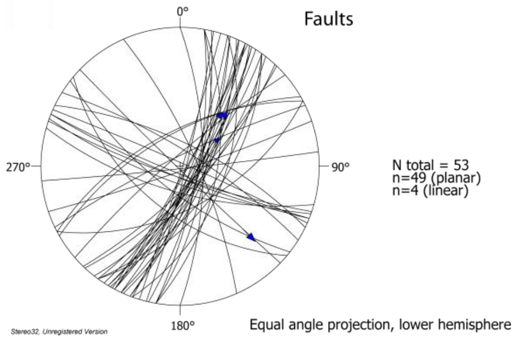
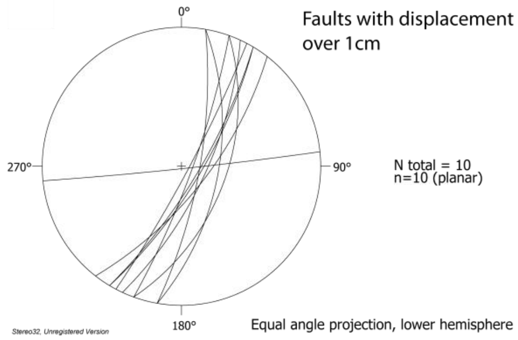
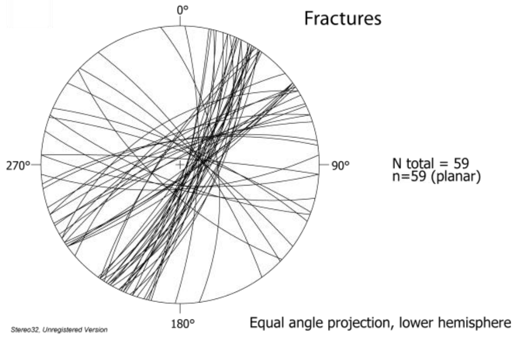
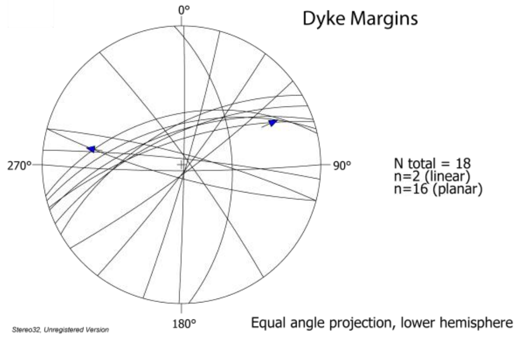


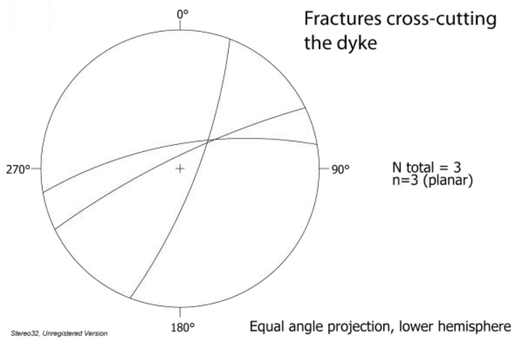
Figure 5.20C. A broken bridge, showing a large amount of fracturing around the dyke tip, supporting the interpretation that many fractures were formed as the dykes intruded. The close parallel between the dyke and basement fabrics is also well illustrated in this image. These stopovers and jogs in the dyke margins are typical of dykes having intruded under horizontal shear stress e.g. Pollard, (1987).

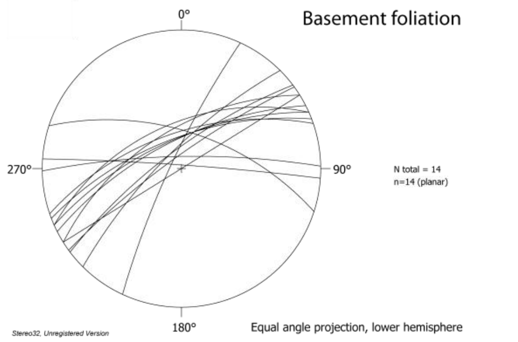












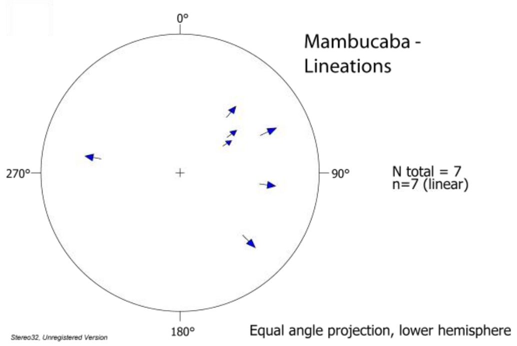


Figure 5.21 Stereonets showing structural data collected at Mambucaba. Stereonets are Equal angle projections. Planes are plotted as black lines, and lineations are plotted as blue arrows.

5.4.1.6 Quatis, RJ

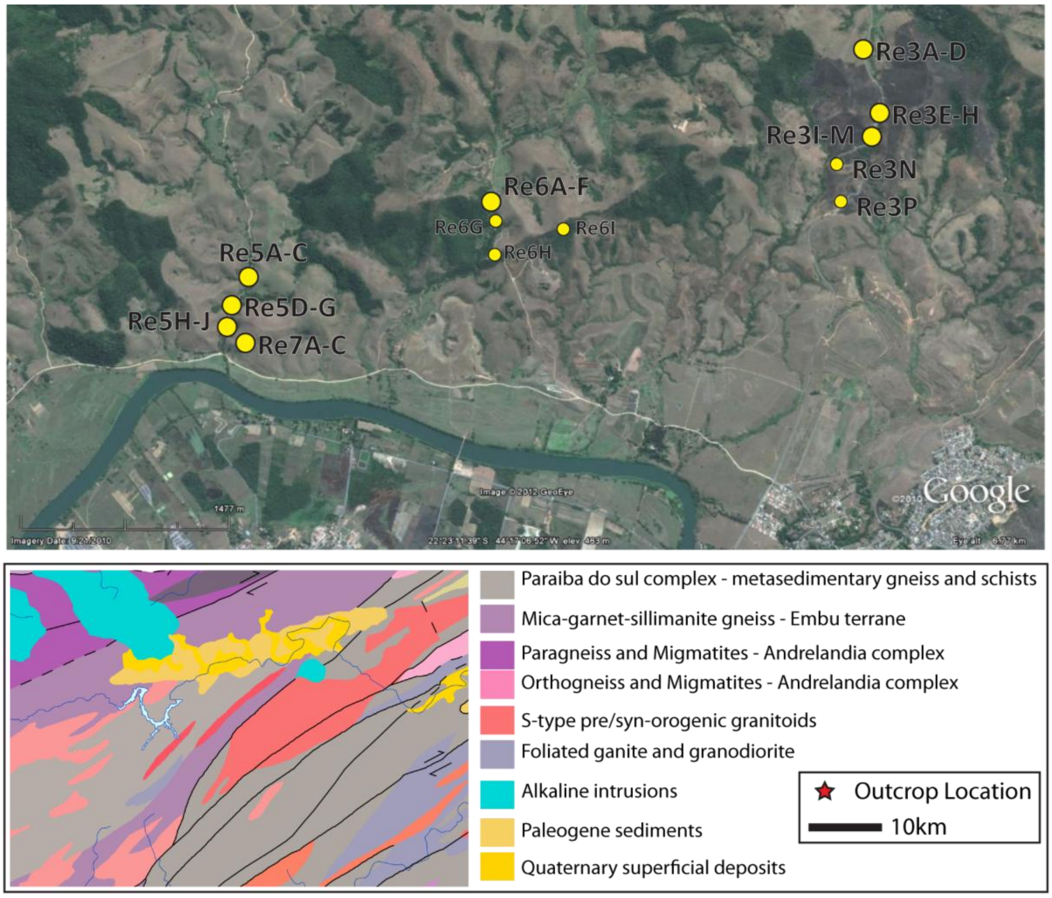


Figure 5.22 A. Google earth aerial photograph of the outcrop region at Quatis, showing the locations of outcrops visited (yellow circles). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

This was the only inland outcrop visited. It consists of a number of exposures of breccias and mylonite in streams and along tracks in farmland and scrubby vegetation. Identification of lithologies was difficult, as the highly weathered and vegetated surface of the rock needed to be removed in order to identify structures (Fig. 5.22A). Distinction of features formed due to tectonics as the fault was formed, and those formed by weathering processes is also highly difficult. The age of the mylonite has not been published.

Outcrop-scale Structures

The outcrop consists of two rock types: high grade blastomylonite and coarse, highly weathered breccia. The host lithology for the mylonite cannot be observed, due to the high level of weathering on inland outcrops. Basement fabrics in the blastomylonite dip in a number of directions (Fig. 5.23C), with some fabrics dipping steeply and trending ENE-

WSW. The majority of basement fabric, however, dips shallowly and displays diverse dip directions. Fracturing in the blastomylonite, away from the breccias displays 3 fracture sets, trending N-S, ENE-WSW (parallel to basement fabrics and NW-SE (Fig. 5.24) Fracturing in the breccia is highly complex; with high and low-angle fractures present (Fig. 5.23A). The majority of fractures are steeply dipping, and appear to trend NE-SW or ENE-SSW, however other fractures trend in almost all directions. Very few structures have been directly identified as faults, although slickenline lineations are present on many fracture surfaces. These lineations display a wide array of plunge directions (Fig. 5.24), although most plunge relatively shallowly. One larger silica-indurated fault was observed, with steeply dipping slickenfibres (Fig. 5.23B). The main fault forms a large ridge, separating the sediments of the Cenozoic Resende basin from the Ribeira belt basement (Fig. 5.23D). This makes it the only lineament which could be identified in the field.

Interpretation

The location of the fault breccias, trending parallel to the mylonite, suggests that the location of the mylonite may have played a role in determining the location of the fault. Without better outcrop it is difficult to be certain, and there are only a few measurements of steeply-dipping foliation (i.e. foliation which is likely to have been reactivated by a steeply dipping normal fault) within the mylonite. The shallow plunges of lineations could suggest an element of oblique deformation on the large fault, although the wide array of fracture orientations makes the kinematics of the fault difficult to define with any certainty.

The indurated and highly altered breccias which make up this fault are typical of faults in the area which are thought to have formed in the post-rift period (Upper Cretaceous-Lower Cenozoic) (Gontijo-Pascutti et al., 2010). Thus, while the fault does suggest reactivation of large basement structures has occurred, it does not show that these mylonites were reactivated during the earliest Early Cretaceous rifting.

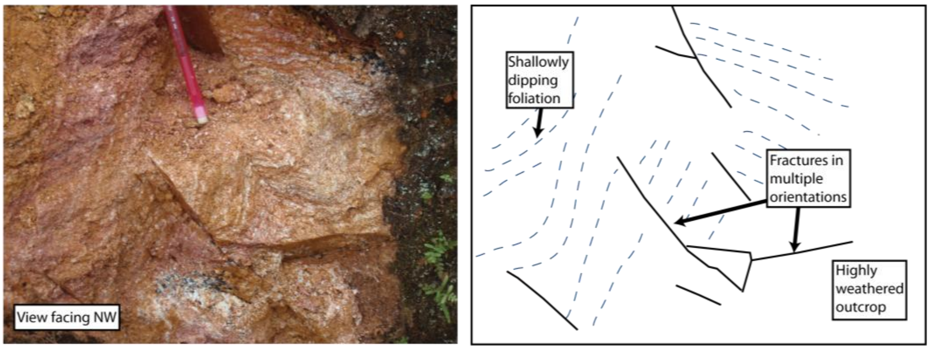


Figure 5.23A. Highly weathered outcrops are found along road sections around Quatis. Fractures often stand out from these, and foliation can sometimes be identified. The quality of the outcrops, however, makes the identification of tectonic features; and distinguishing them from features formed by recent geomorphological processes, very difficult

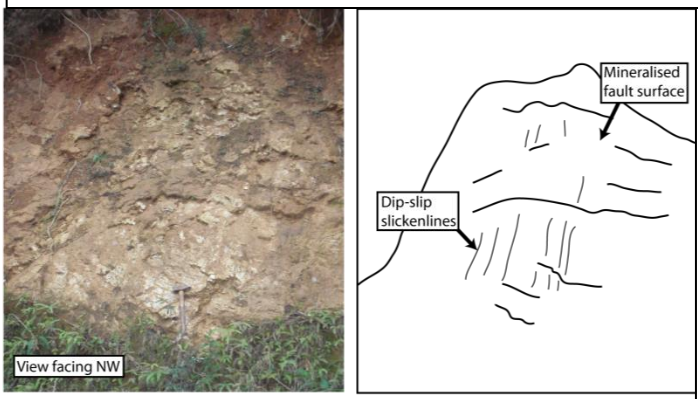


Figure 5.23B. A mineralised fault at Quatis, with dip slip slickenfibres. The fault has been exposed after a recent landslip, and the larger steps visible in the photograph were probably formed as a result of this, rather than by tectonic processes.

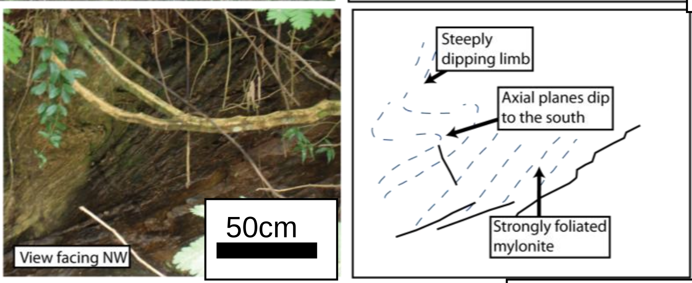


Figure 5.23C. A fold in mylonite basement at Quatis, showing the typical shallow dip, with steep limbs. These limbs are parallel to the dip of the main fault.

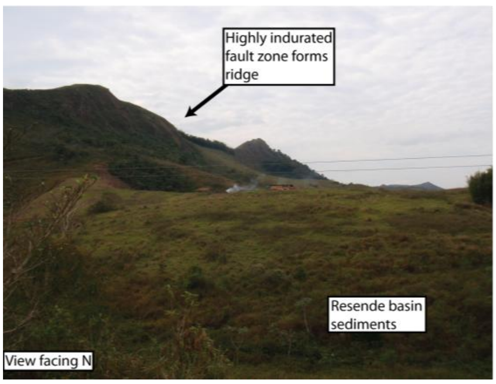


Figure 5.23D. The main fault at Quatis, separating metamorphic basement from the Resende basin sediments to the right of the image. The fault stands above the landscape because the breccia is more resistant to weathering than the sediments or basement, due to silica precipitated along the fault during deformation. This is reported from other faults bounding Cenozoic basins in the area (Gontijo-Pascutti et al., 2010).

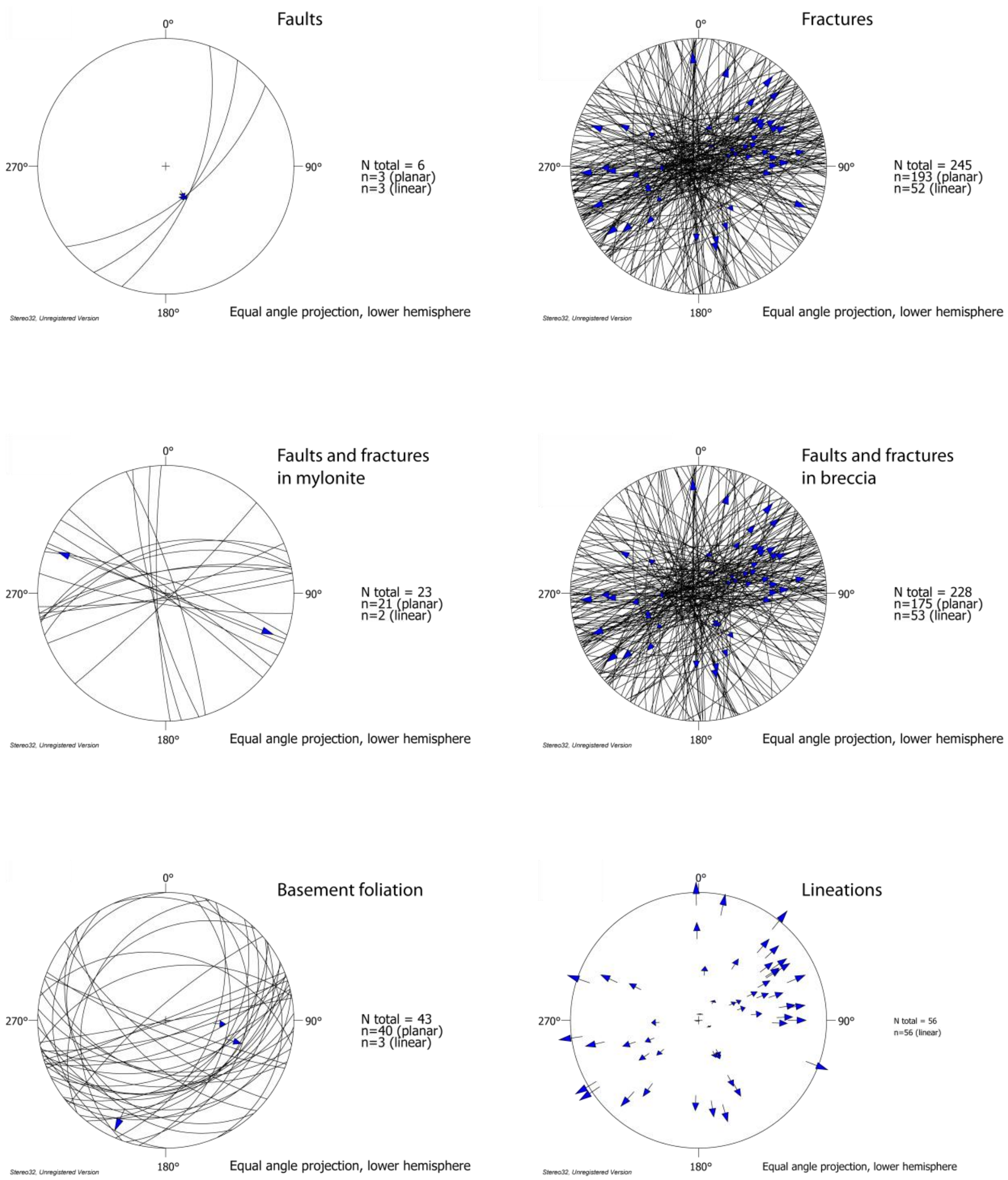


Figure 5.24 Stereonets of structural data collected from Quatis. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.4.1.7 Ubatuba, São Paulo state (SP)

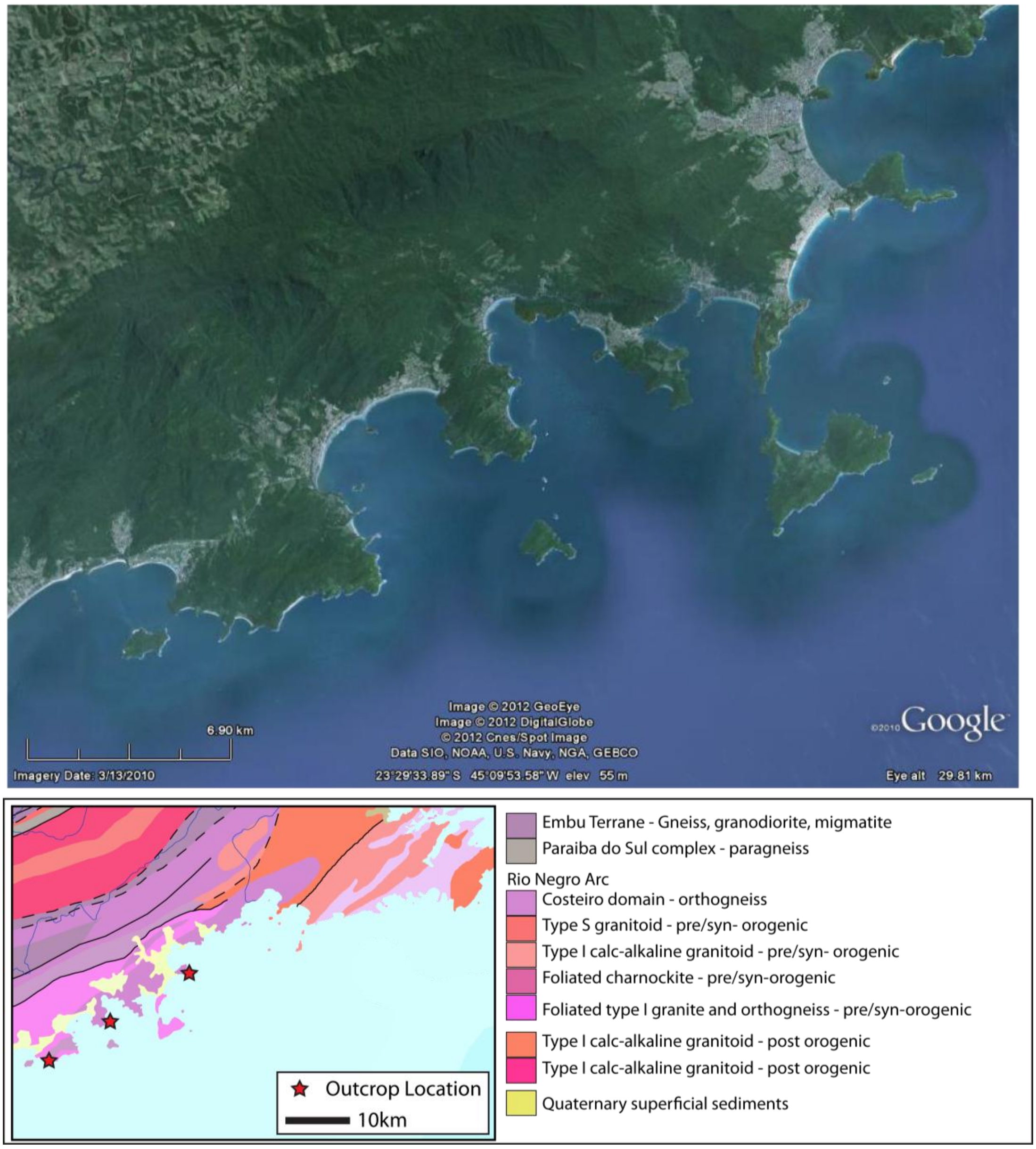


Figure 5.25 A. Google earth aerial photograph of the outcrop region around Ubatuba, showing the regional terrain. The City of Ubatuba is represented by grey areas along the coast. B. geological map of the area, showing key basement lithologies and structures (black lines).

Region Summary

The Ubatuba region consists of a series of outcrops that display fracturing and NE-SW trending syn-and post-rift dykes intruding the Neoproterozoic Rio Negro Arc (chapter 2.3.1.1.10) with various lithologies spread along the coastline around the city of Ubatuba (Fig. 5.25). Each of these outcrops is described individually below.

5.4.1.8 Praia Fortaleza

Figure 5.26 Google earth aerial photograph of the outcrop region at Praia Fortaleza, showing the local terrain, the extent of outcrop, and the locations of outcrops visited (yellow circles).

Outcrop Description

This outcrop consists of a wide, flat expanse of basement exposed on a headland near to the mouth of a sheltered bay (Fig. 5.26). The lithology here is high grade gneiss of the Neoproterozoic Rio Negro magmatic arc, cut by a number of fractures.

Outcrop scale structures

The basement at Praia Fortaleza is Granulite Facies Gneiss, and consists of cm scale mafic and felsic bands. Basement displays a strong ductile structure that is NNE-SSW trending, and dips shallowly to the WSW. Basement foliation does not trend parallel to any of the brittle structures seen at this outcrop.

This outcrop shows a small number of discrete, long (10-25m) faults and fractures exposed in gneissose basement, (Figs 5.27A, B and C). Faults trend NE-SW, dip steeply to both the SE and NW, and show steeply-plunging slickenline lineations (Fig. 5.28). Fractures show a wide array of strikes, with two main sets trending NE-SW and N-S, although there are many fractures with other trends. Fractures typically dip steeply, although a small number of shallowly-dipping fractures are observed. Towards the western end of the outcrop, fracturing is more intense, with two sets of steeply dipping fractures observed, also trending N-S and NE-SW (Fig. 5.27B). Cross-cutting evidence for the fractures cannot be observed.

Interpretation

This outcrop highlights the NE-SW trend of faults across the Serra do Mar, even where dykes are not present.

The shallowly-dipping fractures in shallow-dipping basement could suggest a local basement influence, although being irregular and open, these fractures display a very different character to other fractures at this outcrop, and therefore may have formed as a result of the 'onion skin' weathering that is typical across the region. The steeper-dipping faults show both steeply-plunging slickenlines suggesting dip-slip, and Riedel shear-type geometries (Fig. 5.27A), which suggest an oblique element to the deformation.

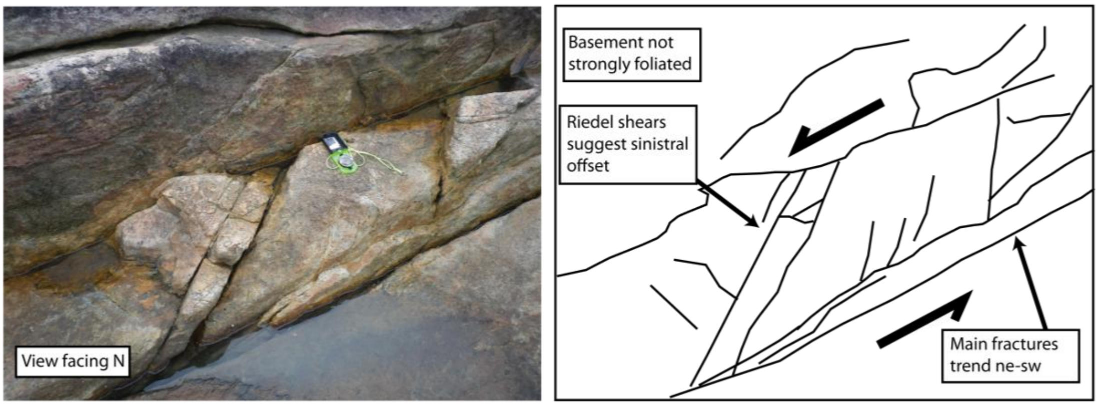


Figure 5.27 A. The largest fracture at Praia Fortaleza can be followed along the entire length of the outcrop at locality U7. In places it is a single discrete structure, though it locally branches into 2 parallel structures, with Riedel type fractures linking them, forming sinistral geometries. The basement here is weakly foliated, and not reactivated by this structure.

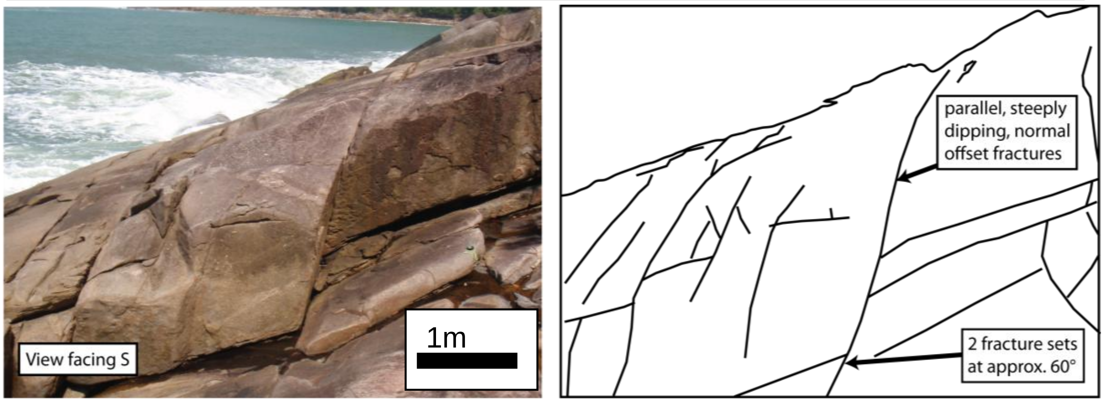


Figure 5.27B. At locality U8, two sets of steeply dipping fractures can clearly be seen. These fractures are found a short distance along strike from the large fracture seen in fig.5.32A. This highlights the local variations in structural style that may relate to basement influence, or possibly relates to proximity to other major structures, such as dykes.

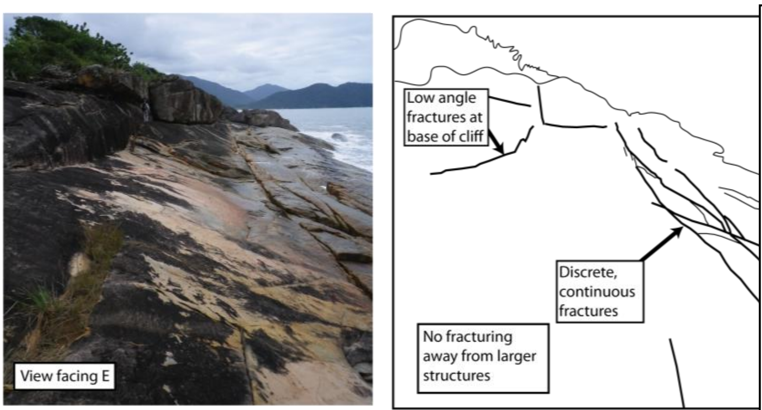


Figure 5.27 C. The long discrete fractures at locality U7 at Praia Fortaleza, with relatively little deformation between them. Lower angle fractures appear to reactivate basement fabrics, though it is unclear if these are tectonic, or formed due to exfoliation type weathering during regional uplift.

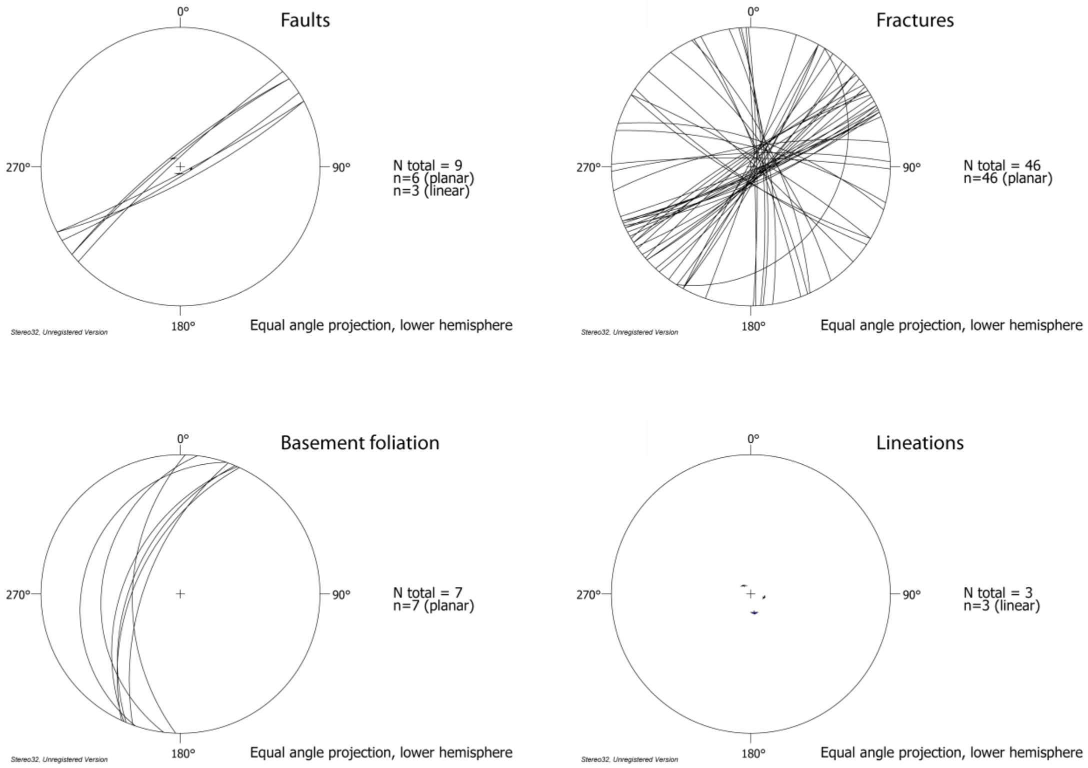


Figure 5.28. Stereonets showing structural data from Praia Fortaleza. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows

5.4.1.9 Ponta Grossa

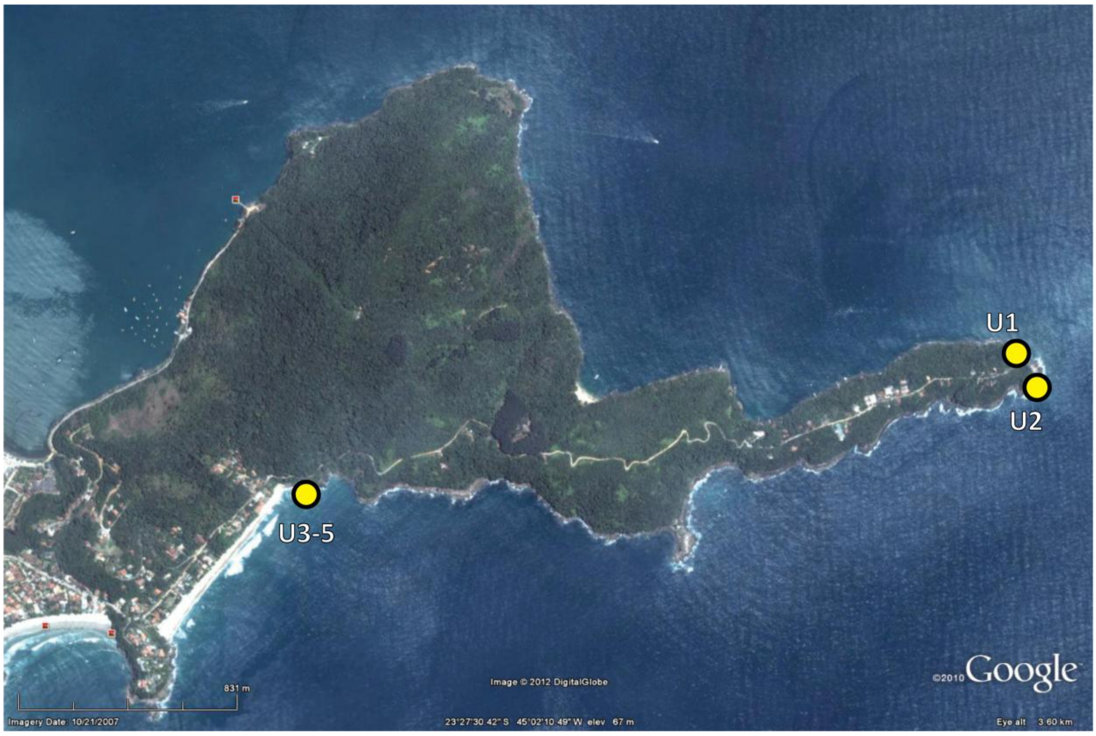


Figure 5.29 Google earth aerial photograph of the outcrop region at Ponta Grossa, showing the local terrain and the locations of outcrops visited (yellow circles).

Outcrop Description

Ponta Grossa is a large headland on the coast near to the centre of the city of Ubatuba. Outcrops are exposed around the headland (U1 and U2 on Fig. 5.29), and a further small outcrop can be seen at Praia Vermelha (U3-5 on Figure 5.29) to the southwest of the headland. The outcrop at Ponta Grossa is composed of granitic gneiss. Basement foliation is variable across the outcrop. 2 large NE-SW trending syn-rift dolerite dykes and one smaller, NE-SW trending post-rift lamprophyre dyke (see chapter 2.4 for discussion of the different syn- and post-rift intrusive events on the margin) here highlight the geographical coincidence of the post-rift alkaline and syn-rift tholeiitic dyke swarms in the Ribeira belt.

Outcrop-scale structures

2 large (3m and 5m widths) dolerite dykes, and one lamprophyre dyke can be observed at Ponta Grossa (Figs 5.30A and 5.30B). All trend NE-SW, within a few degrees of dip and strike from each other, regardless of composition. The lamprophyre dyke contains 1-2mm vesicles. Faults and fractures trend parallel to the dykes. Both faults and fractures show strong NE-SW trends although fractures with other orientations can also be observed (Fig. 5.31). The only lineation measured is a slickenline, which plunges relatively shallowly to the

NE. Only one fault and a small number of fractures are observed parallel to basement foliation (Fig. 5.30c) which shows some variation in dip and strike across the outcrop. Fractures can be observed to cut the dyke at Praia Vermelha (U3-5 on Figure 5.29), parallel to joints observed within the dyke. Cross-cutting relationships between fractures could not be determined, as they typically do not show any observable offset. Away from the dykes, the density of fracturing and faulting appears to be lower, with larger, more discrete fractures as opposed to the more closely spaced fractures observed near the dykes.

Interpretation

Although a few examples of small-scale basement influence were found at Ponta Grossa, the development of the larger structures, especially dykes, has not obviously been strongly influenced by local basement fabrics. The dominant NE-SW structural trend, common to the different events is highlighted here, with both doleritic and lamprophyre dykes observed trending parallel to one another. Both the early dolerite and later lamprophyre dykes were also observed with contacts parallel to fractures, showing that similar intrusive relationships to those observed between rift-related structures can be observed in post-rift structures, and that both syn-and post rift dykes are controlled by the location and orientation of pre-existing fractures. The margin of the larger dolerite dyke at Praia Vermelha appears to have been reactivated by later structures (Fig. 5.30A), showing that these dykes may have influenced deformation after their cooling.

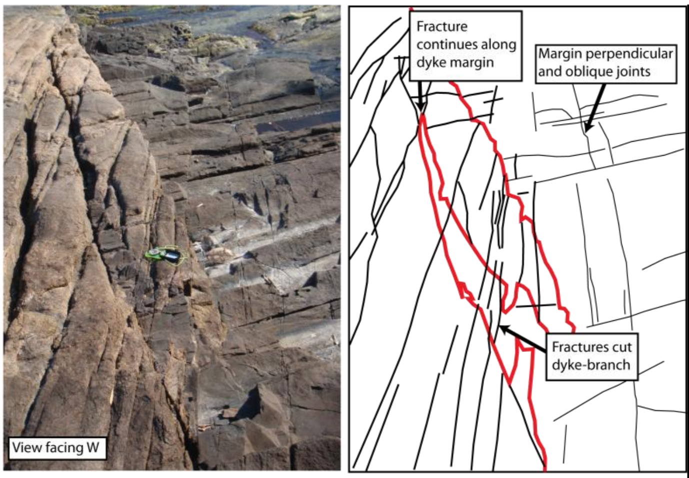


Figure 5.30A. The southern margin of the dolerite dyke at wpU4 at Ponta Grossa, showing a small branch parallel to fractures in the basement. Other fractures trend oblique to the dyke, and cross cut it in places. Apparent joints within the dyke have two trends; one perpendicular to the dyke margin, and the other parallel to the fractures which cut the dyke.

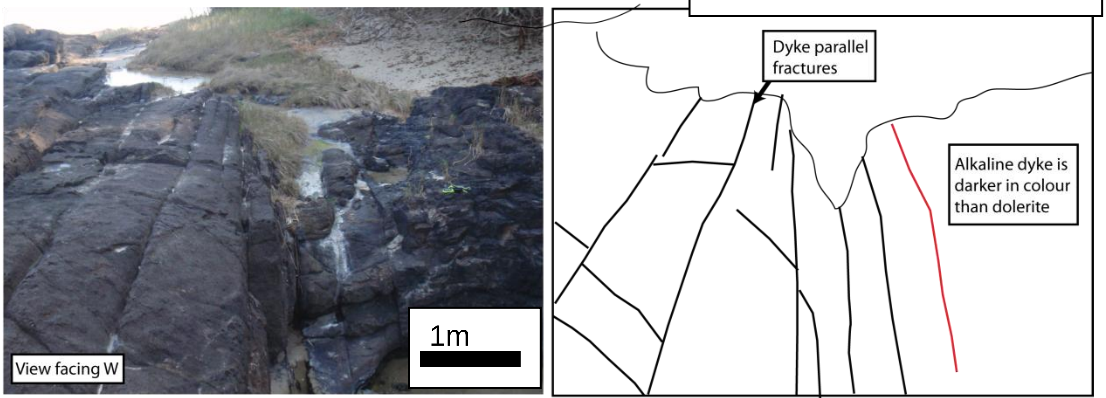


Figure 5.30B. The lamprophyre dyke at wpU5, showing strongly dyke-parallel fracturing, and its darker weathering, which is used as a basic way of distinguishing these dykes in the field. Basement here is very poorly foliated, in contrast with basement at U1 and U2, highlighting how local variations in basement structure have little impact on the geometries of larger structures.

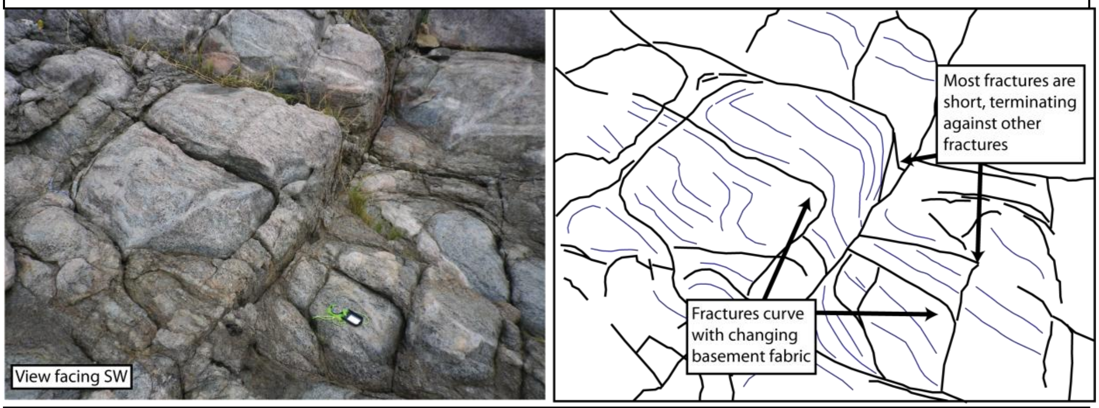
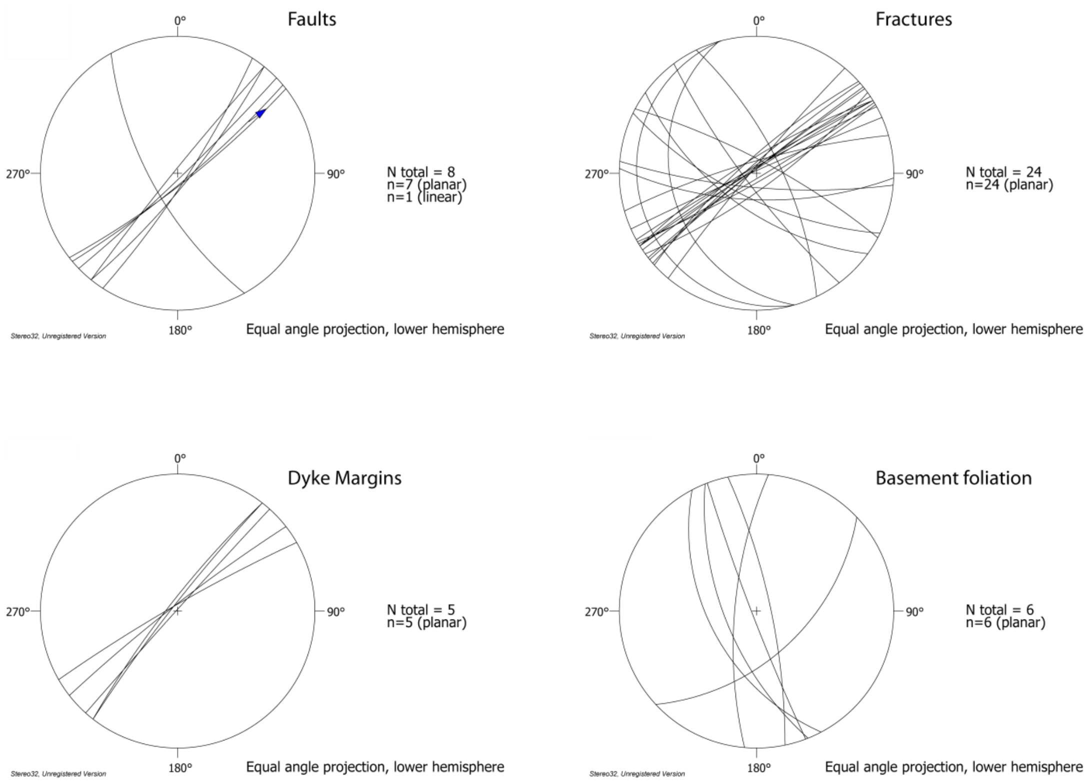


Figure 5.30C. At wpU1, local basement influence can be seen at Ponta Grossa, with complex basement structure affecting the outcrop pattern of fractures. Where basement is strongly foliated, fractures curve parallel to the foliation. Where foliation is weak or non-existent, fractures tend to be more continuous and less curved. Many smaller fractures appear to terminate against one another, rather than being crosscut.



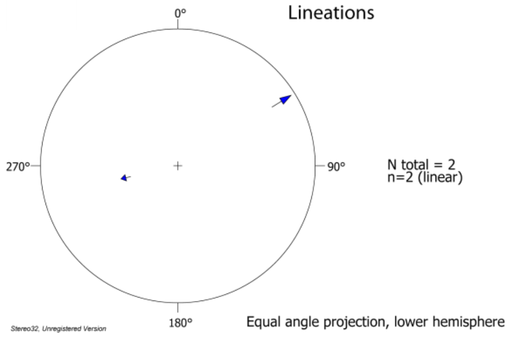


Figure 5.31. Stereonets of structural data collected at Ponta Grossa. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.4.1.10 Praia Sununga

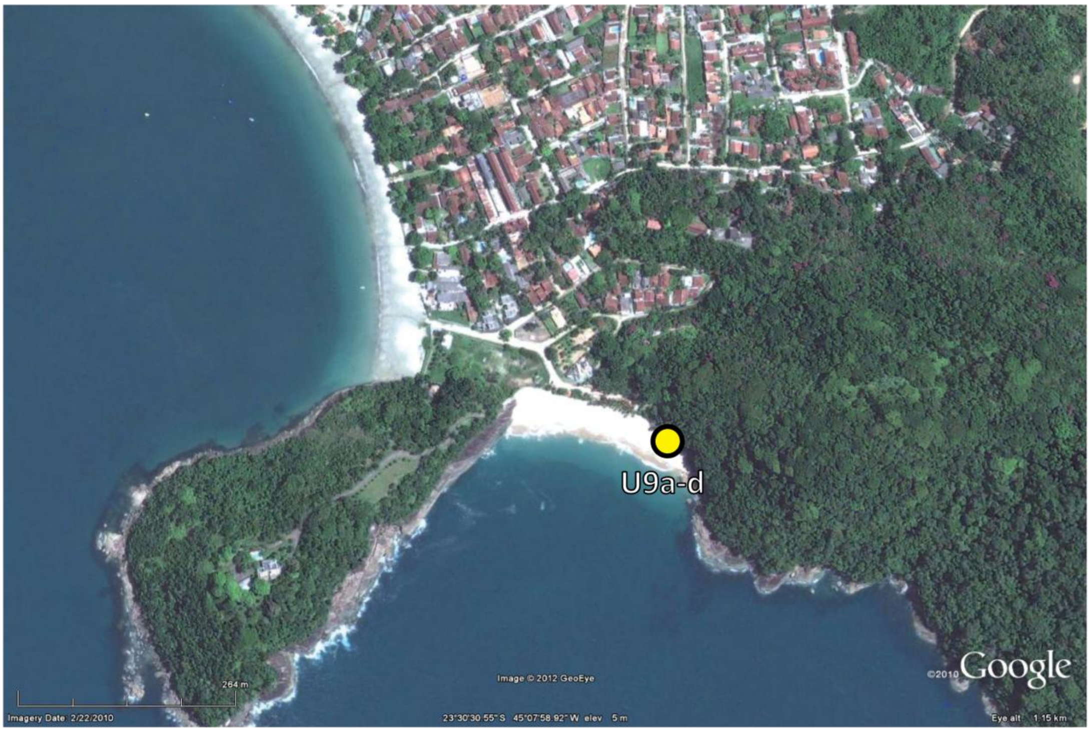


Figure 5.32 Google earth aerial photograph of the outcrop region at Praia Sununga, showing the local terrain and the location of the outcrop visited (yellow circles). The majority of the outcrop is found under trees, and is not easily identifiable on aerial photographs.

Outcrop Description

Praia Sununga is a small beach to the west of the city of Ubatuba. Small outcrops at the eastern end of the beach are exposed to waves, but offer good exposure of high grade Neoproterozoic gneissose basement (Fig. 5.32). Three, broadly NE-SW trending small (30cm-1m wide lamprophyre dykes are exposed, with one in particular exposed in the roof of a cave (Fig. 5.33A). The dykes are assumed to belong to the post rift alkaline event on the basis of their composition.

Outcrop-scale structures

The basement at Praia Sununga is a granulite facies Gneiss. The basement is relatively strongly foliated and crosscut by pegmatite veins. Basement foliation trends WNW-SSE. Steeply-dipping dyke-parallel NE-SW-trending faults show steeply-plunging slickenlines (Fig. 5.34). The faults also dip parallel to the margins of one 80cm wide dyke (Fig. 5.33B) although the margins of another 50cm wide dyke (seen in a cave roof) dip in the opposite direction to the faults (Fig. 5.33A). A third dyke is 30cm wide, and can be observed to have necked as it intruded past a small (15cm wide) pegmatite vein in the basement (Fig. 5.33C). The necked dyke (Fig. 5.33C) also intrudes parallel to basement fabrics, which is clearly different from the dyke in the cave roof (Fig. 5.33A), whose intrusion is apparently unrelated to basement structure. The presence of fractures within a block of basement in one of the dykes suggests that this outcrop was fractured at some point before the intrusion of the dykes (Fig. 5.33B).

Interpretation

The faults do not appear to have been influenced by any basement fabrics or structures. The dip-slip slickenlines on the faults here suggest extensional offset (while these structures could be reverse faults, this conclusion is inconsistent with the regional geology) and they are most likely to be normal faults. The observation of dip-slip slickenlines shows that outcrops can display different kinematics within a relatively small area. The composition (and therefore age) of the dykes here show that these dip slip kinematics are likely to relate to a post-rift event. The difference in strike and intrusion style between the dyke in the cave roof and the dyke trending parallel to basement fabrics could indicate that they formed during different events, although their similar petrology suggests they may be of equivalent age.

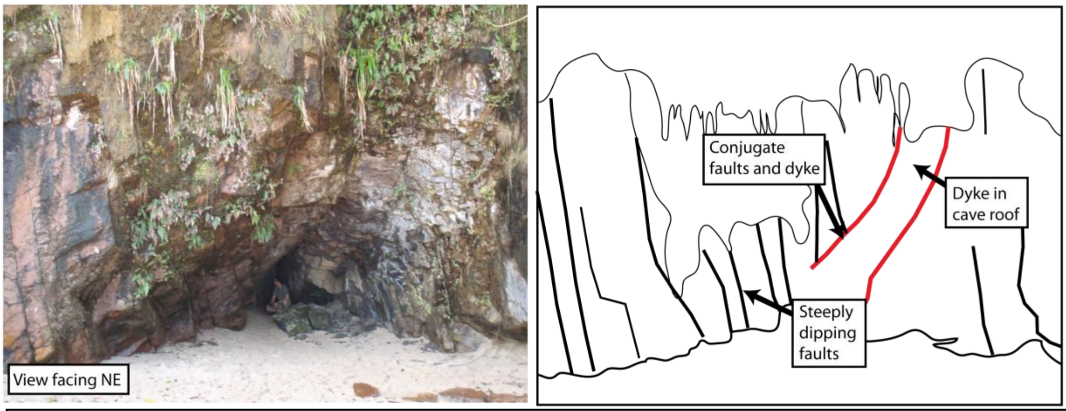


Figure 5.33A. This dyke is exposed in the roof of a cave at Praia Sununga, with steeply dipping faults showing dip slip slickenlines making up the wall of the cave. The dyke and the faults have similar strikes, but dip in opposite directions, possibly suggesting that they are conjugate, or that the dyke intruded late, cutting the faults.

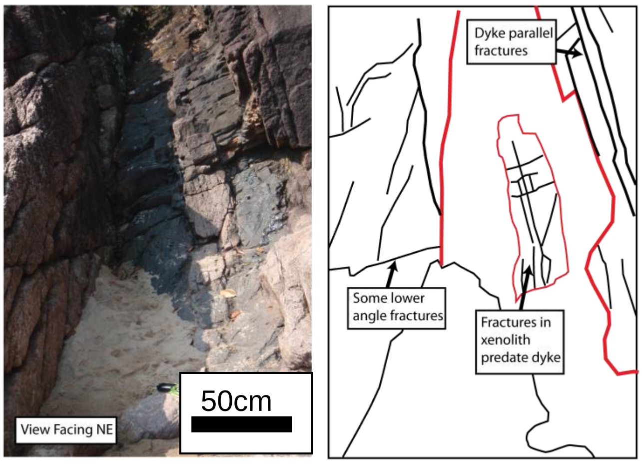


Figure 5.33B. Another dyke at Praia Sununga, containing a xenolith of gneissose basement. This xenolith is elongate parallel to the dyke margins, and parallel to fractures in the country rock. Fractures in the xenolith are also parallel to these, and do not continue into the dyke, suggesting they were present prior to the dykes intrusion. Some lower angle fractures are also seen here.

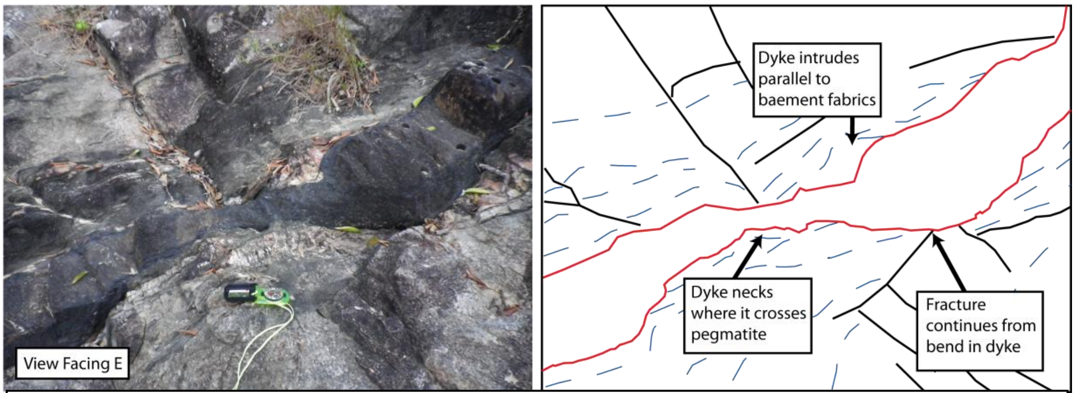
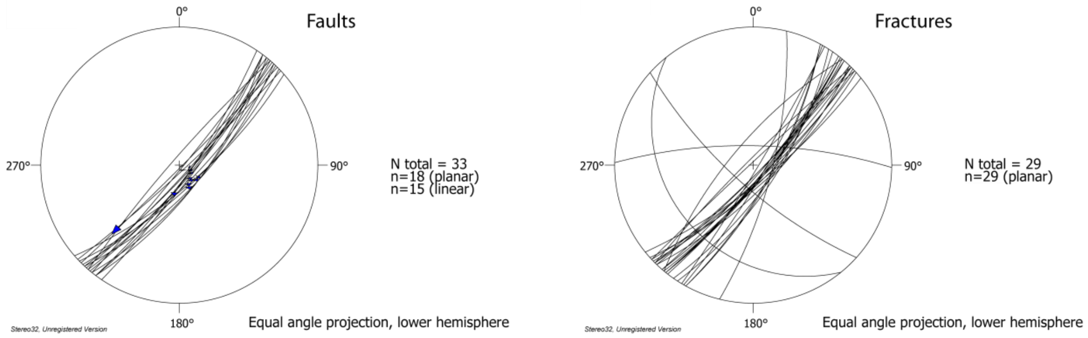
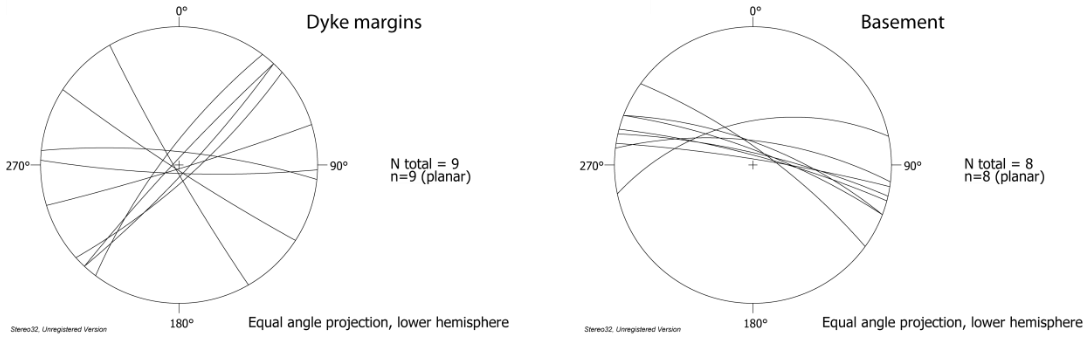


Figure 5.33C. A third small dyke can be seen at Praia Sununga. It trends at a relatively high angle to the other dykes here, and parallel to local basement fabrics. It necks where it crosses a pegmatite intrusion, indicating a high degree of basement influence on this particular structure. Where the dyke bends, fractures parallel to its margins, possibly suggesting it intruded along them. Other fractures appear unaffected by basement structure, and do not cut the dyke.





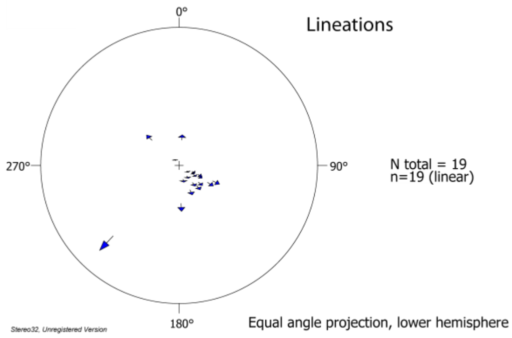


Figure 5.34. Stereonets of structural data from Praia Sununga. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.4.1.11 Caraguatatuba

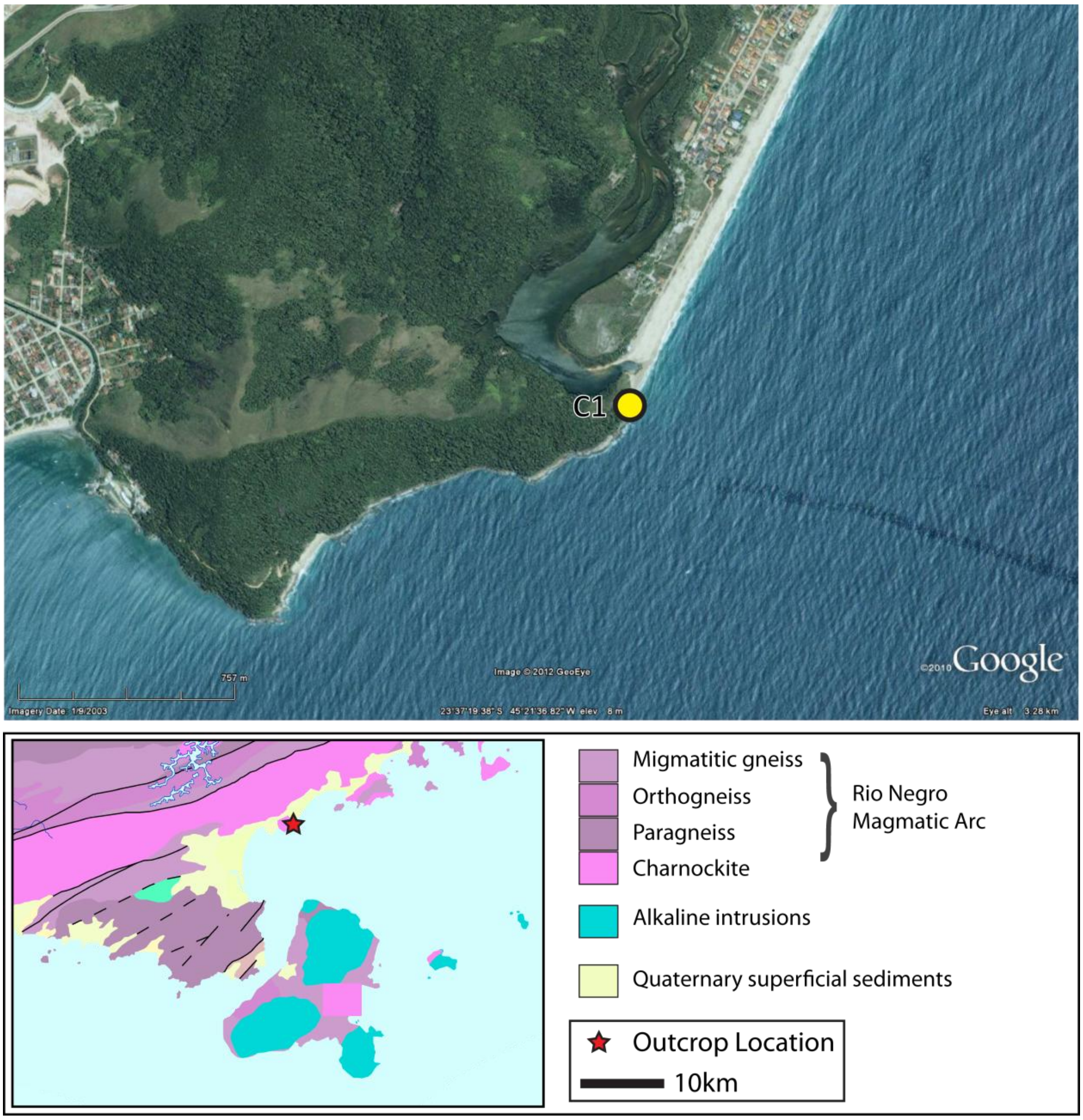


Figure 5.35 A. Google earth aerial photograph of the outcrop region at Caraguatauba, showing the regional terrain, and the locations of the outcrop (yellow circle). B. Geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

A small, high headland is exposed at the western end of a large beach to the south of Caraguatatuba (Fig. 5.35A). The headland comprises strongly foliated Neoproterozoic granitic gneiss (Fig. 5.35B), with lenses of more mafic material, and with a steeply-dipping ductile fabric. A number of fractures cut the basement, but larger structures such as faults or dykes were not observed here.

Outcrop- scale structures

Basement fabrics are strongly planar, but not strongly heterogeneous in terms of composition. NE-SW striking, steeply-dipping fractures and basement foliation are parallel (Figs 5.36, 5.37), with only a few fractures observed cross-cutting basement fabrics. Two 5cm wide quartz veins were observed, with contacts that are not parallel or sub-parallel to either basement fabrics or brittle fractures. The fact that one vein is observed being cut by a fracture which cuts basement fabrics suggests that they may have formed during an earlier event than the rest of the fractures here. No fault rocks or high offset faults were observed at this outcrop.

Interpretation

This outcrop shows basement-influenced fracturing, although no evidence for significant extension or offset along any of the fractures (Fig. 5.36) was observed. No dykes were observed at this outcrop, and thus the age of fracturing is unknown. There is no evidence at this outcrop that the intensity of fracturing here is greater than at other outcrops, and, due to the lack of observable offsets on faults, it is impossible to say whether more deformation has been accommodated Based on observations of fractures in similar orientations at outcrops across the region, it is difficult to judge whether the orientation of fractures here is controlled by basement, or whether the fractures would be in the same orientation if the basement was absent or trended in a different direction.

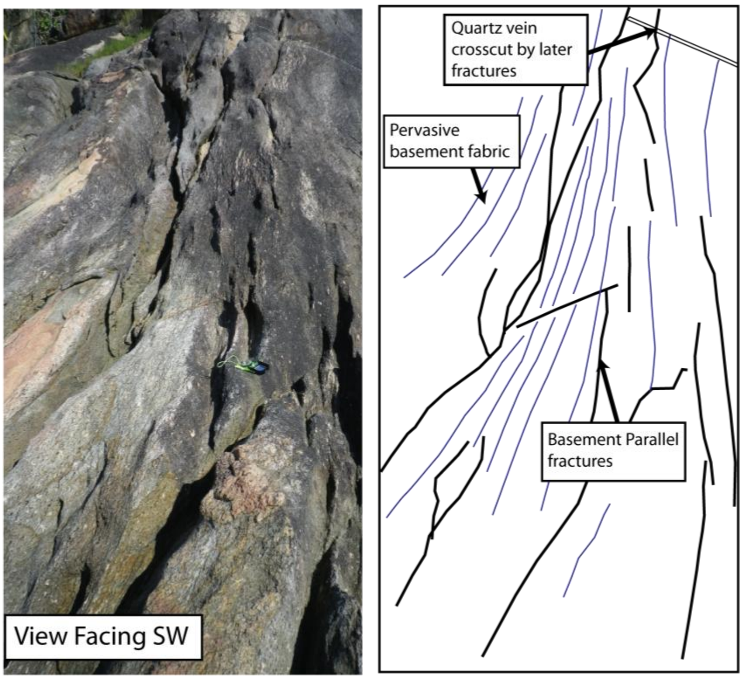


Figure 5.36. Weakly foliated basement is reactivated at Caraguatatuba. This locality has steeply dipping, NE-SW trending basement. The longest fractures trend parallel to this basement, and have no identifiable offset. No fault rock or lineations are seen on any of these fractures, highlighting that despite local reactivation, large amounts of deformation are not always seen.

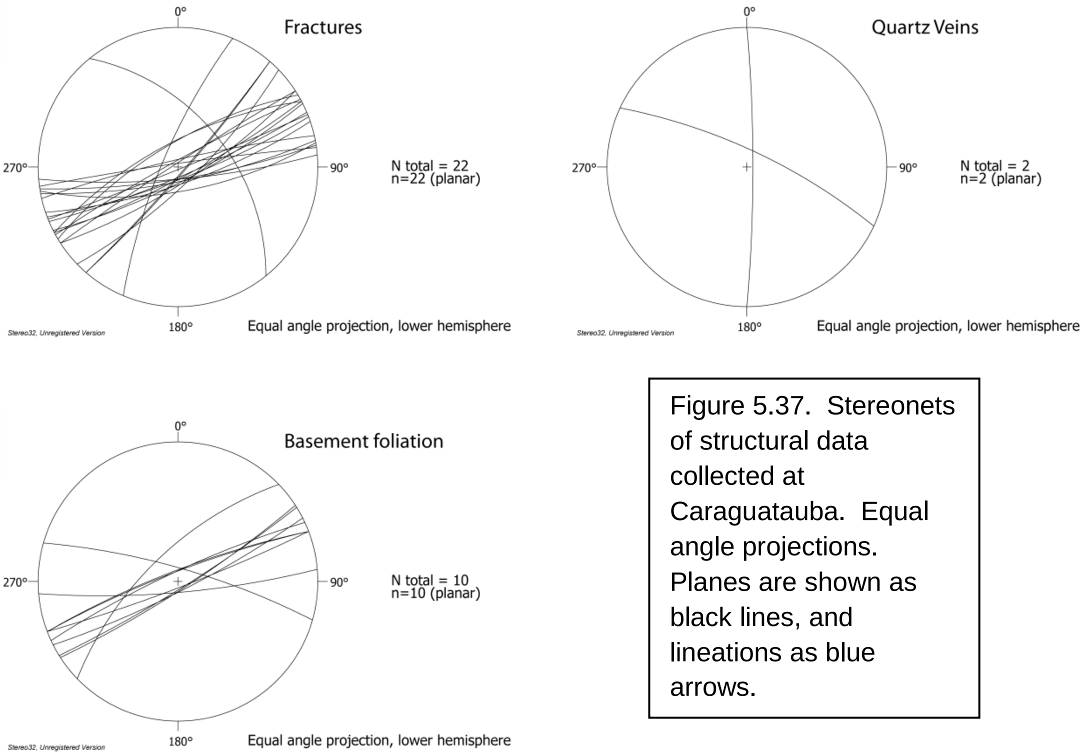
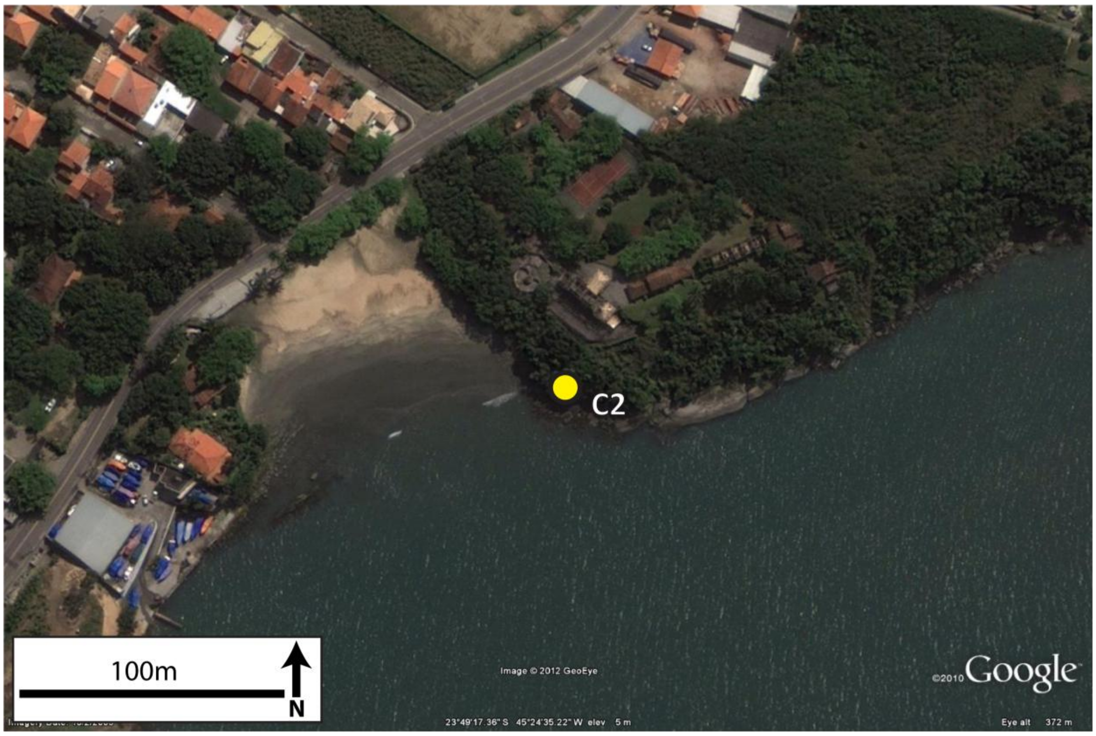


Figure 5.37. Stereonets of structural data collected at Caraguatauba. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.4.1.12 São Sebastião



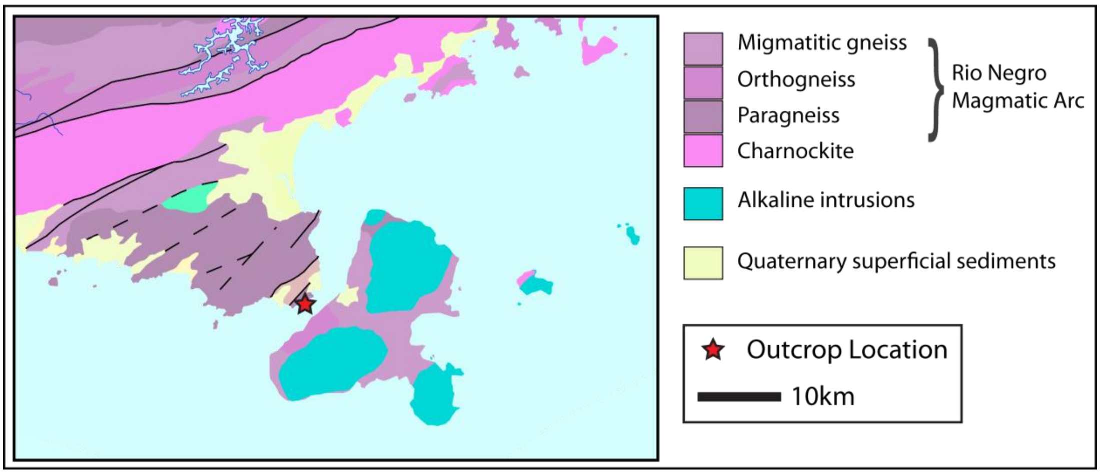


Figure 5.38 A. Google earth aerial photograph of the outcrop region at São Sebastião, showing the regional terrain, and the locations of the outcrop (yellow circle). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

Two small outcrops were studied on either side of a small bay in the town of Sao Sebastiao (Fig. 5.38A). The basement is composed of similar gneissose lithologies to that observed at Caraguatatuba (above), with a small NE-SW trending dolerite dyke intrusion and a number of fractures and faults exposed.

Outcrop-scale structures

To the eastern side of the small beach, basement fabrics are steeply to moderately SE-dipping and NE-SW-trending. To the western side of the beach, the basement structure is very different, with a more shallowly dipping, and better developed foliation (Fig. 5.39A). Basement foliation on the western side of the bay trends N-S, and dips moderately westwards. A small, 50cm wide ENE-WSE-striking dyke was observed at this outcrop (Fig. 5.39B). a syn-rift age is inferred for the dyke, because of its doleritic composition. Brittle structures consist of faults with small amounts of offset (<5mm, where seen) and fractures.

The dyke margins are ENE-SSW trending parallel to a number of fractures, although the majority of fractures (90%) trend NE-SW (Fig. 5.40). Joints in the dyke were observed parallel to a number of the NNE-SSW fractures in the basement. 2 faults were recorded from the western side of the bay, and they trend sub-parallel to many of the other fractures in the outcrop. On the eastern side, basement foliation dip steeply and trend NE-SW parallel to many fractures (Fig. 5.40). Only one slickenline lineation was observed, plunging moderately to the west.

Interpretation

In contrast with Caraguatatuba, where a dyke was not observed, fractures here are more abundant, and less strongly related to basement fabrics, which generally dip less steeply. Basement fabric orientation varies either side of the bay, but the orientations of faults and fractures are similar throughout suggesting that there was little influence of basement foliation on the development of brittle structures at this outcrop. Much like outcrops observed in other parts of the Serra do Mar, the faults and fractures trend roughly parallel to a dyke, and are possibly later than syn-rift in origin, suggesting that the relationships between dykes, faults and fractures are important throughout the development of south-eastern Brazil.

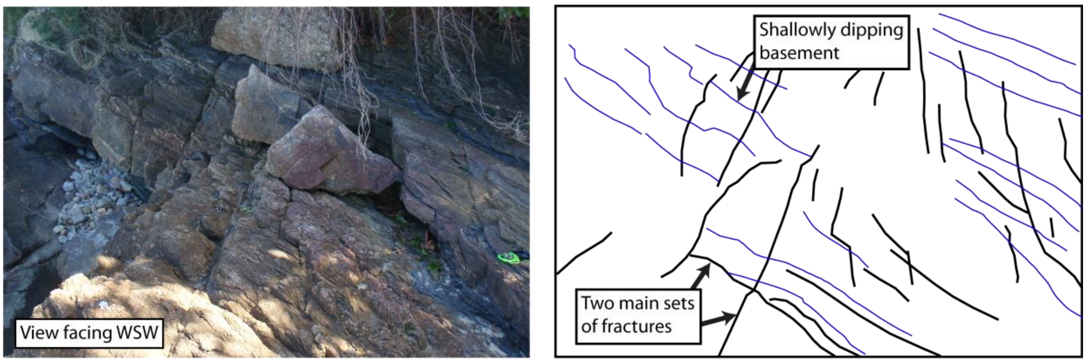


Figure 5.39 A. Fracturing on the western side of the bay at São Sebastião. Fracturing in this relatively strongly foliated, shallowly dipping basement does not appear to be controlled or influenced by basement structure. Two sets of fractures here contrast with the dyke parallel fractures seen across the bay.

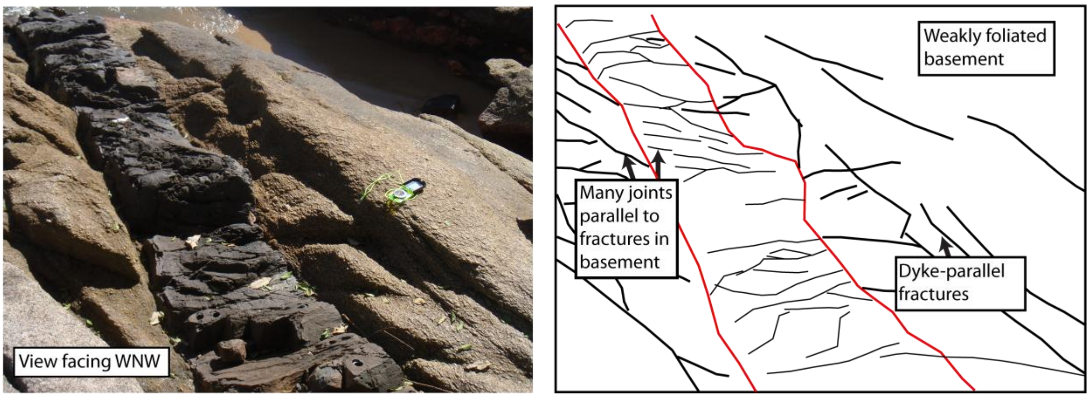


Figure 5.39B. The small dyke and associated fracturing on the eastern side of the bay at São Sebastião. While many apparent joints within the dyke are perpendicular to its margins, others are not, and many are parallel to a fracture set seen in the basement. The other major set of basement fractures trends parallel to the dyke. On this side of the bay, the basement is weakly foliated, but relatively steeply dipping.

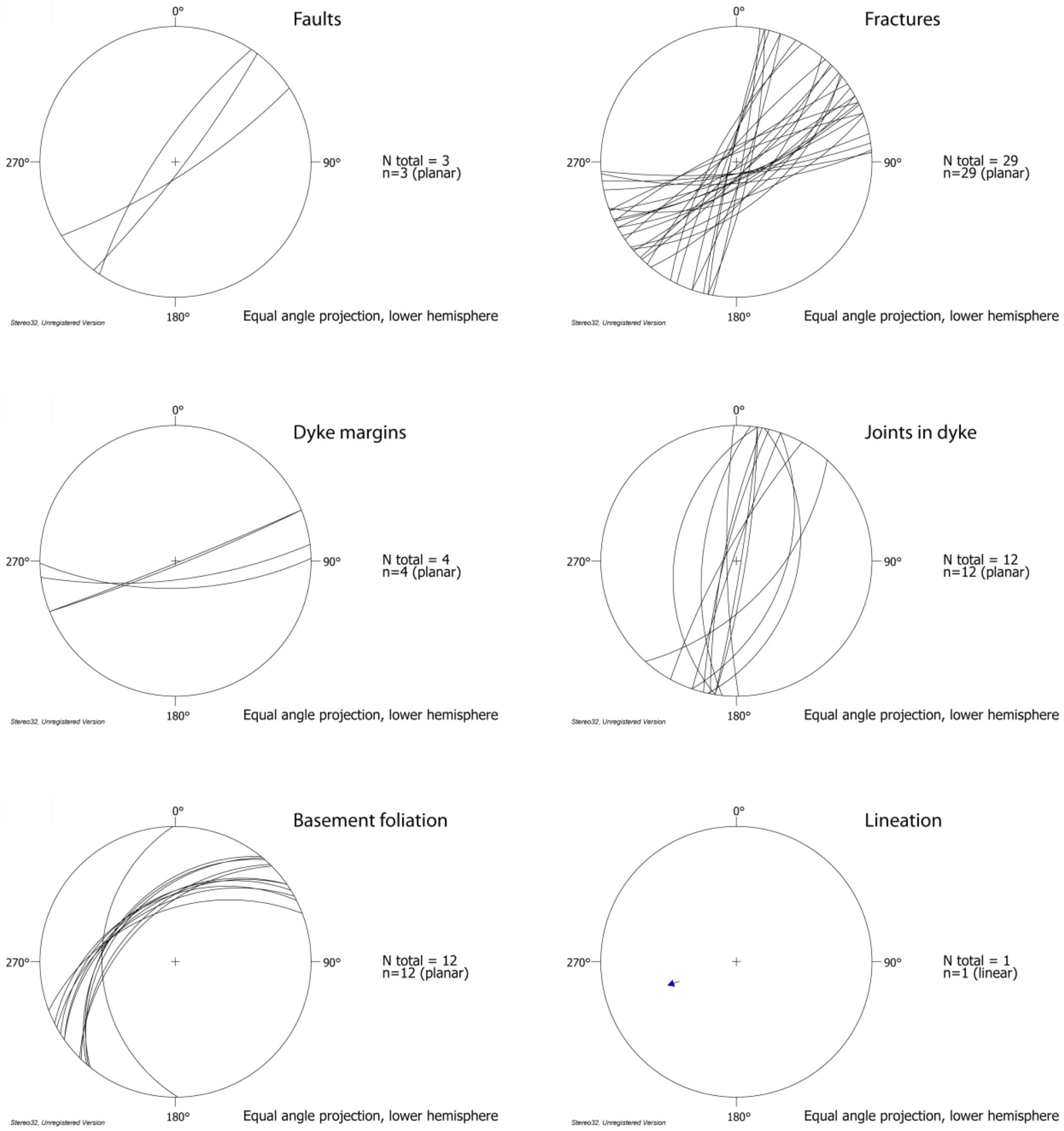


Figure 5.40. Stereonets of structural data collected at São Sebastião. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.4.1.13 Guarujá, SP

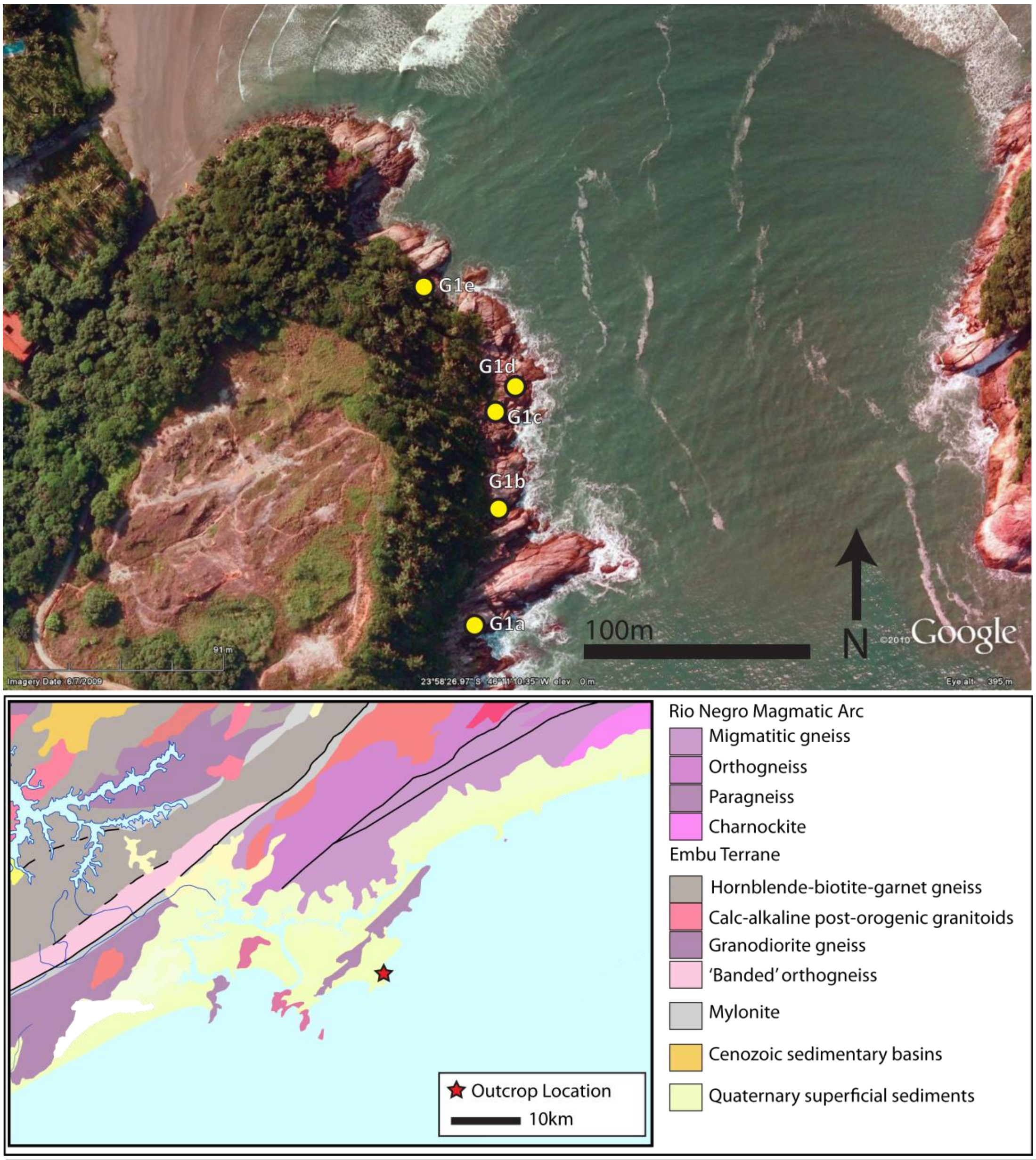


Figure 5.41 A. Google earth aerial photograph of the outcrop region at Guarujá, showing the regional terrain, and the locations of the waypoints visited (yellow circles). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

This outcrop is found by a small river outlet in Guaruja. The outcrop is approximately 200m long, and exposure is continuous and extensive. The outcrop is segmented by a series of NE-SW trending gullies (Fig. 5.41A). The outcrop shows Neoproterozoic gneissose basement of the Rio Negro Magmatic arc (chapter 2.3.1.1.10) with steeply-dipping NE-SW trending fabrics (Fig. 5.41B). A small dyke, a few faults, and numerous fractures cut the basement. Based on its doleritic composition, the dyke is likely to be syn-rift.

Outcrop-scale structures

The basement is quartzofeldspathic gneiss with mafic layering on a 10-20cm scale. The foliation dips steeply to the southeast, and varies between highly foliated regions and more folded, less strongly foliated zones (Figs 5.43B, C). The strongly foliated regions appear to contain a higher proportion of mica than those areas with less strong foliation, and are most likely ductile shear zones (Fig. 5.42A,B,C). Few faults were observed, typically only showing a few millimetres of offset, although zones of higher density fracturing were observed across the bay on a small island several hundred metres along strike (Fig. 5.42A), suggesting that larger scale structures are present here. Where identified, faults show sinistral strike-slip offsets and moderately-plunging lineations.

Both faults and fractures fall into three main sets, trending NNE-SSW, ENE-SSW, and NW-SE (Fig. 5.44). The dyke margins are NE-SW, therefore trend between two of the dominant fracture sets, and sub-parallel to basement fabrics. Foliation measured was relatively consistent in orientation, although there are local variations(e.g. Figure 5.43A,B,C). The fractures and faults which are parallel to basement fabrics almost all occur within the shear zones, whereas those which cut basement outside the shear zones do not, forming N-S-trending, steeply-dipping sets. (Fig. 5.43A). Lineations plunge moderately, consistent with oblique deformation. The most steeply-plunging lineation is found on an ENE-SSW fault.

Interpretation

The outcrop at Guarujá shows strong influence of basement fabric on both the orientation and distribution of brittle structures. High strain, strongly foliated zones within the basement fabrics are apparently reactivated by later brittle fractures and faults, with the highest densities of brittle fracturing occurring in the higher strain zones (Figs 5.42A, B, C). The dyke at this outcrop also appears to reactivate one of these zones (Fig. 5.42B). The dip of the basement fabric at this outcrop also appears to have a significant effect on the development of later fractures, as does mineralogy, with fractures preferentially developing in more micaceous rocks.

A key finding from the outcrop at Guarujá is that where basement anisotropy is potentially easy to reactivate, such as in the strongly micaceous shear zones, structures dip and strike parallel to the basement fabric. Outside these regions, the brittle structures trend closer to N-S, and would lie at a high angle to the predicted regional extension direction (defined as E-W, based on oceanic fracture zones).

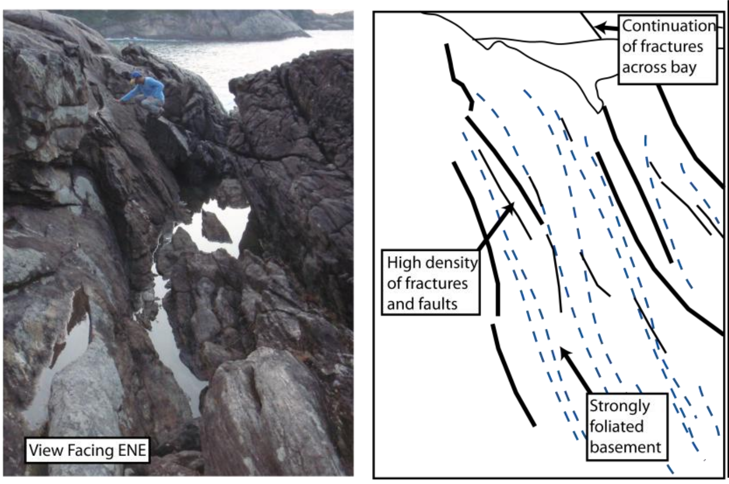


Figure 5.42A - Brittle fracturing and basement fabrics are strongly parallel at Guarujá, and basement fractures are planar. Across the bay, a continuation of this structure can be seen directly along strike.

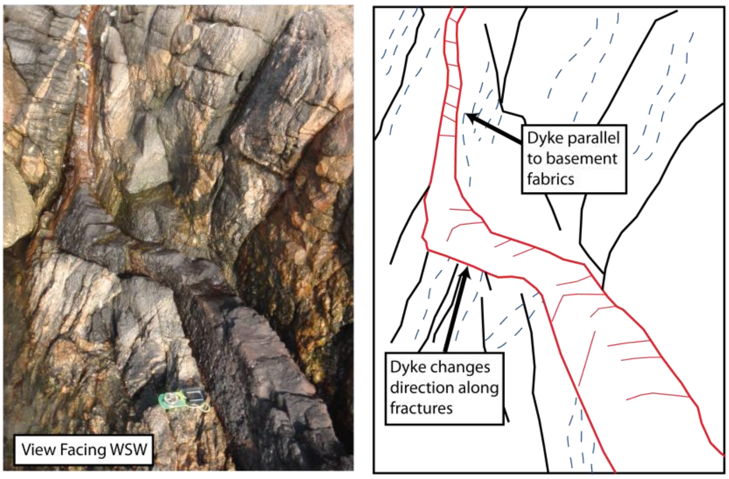


Figure 5.42 B. The small dyke at Guarujá is intruded along a basement shear zone. Whiile the dyke does change direction by 10-20°, it broadly parallels the basement fabrics, and also brittle fractures which appear to reactivate basement fabrics.

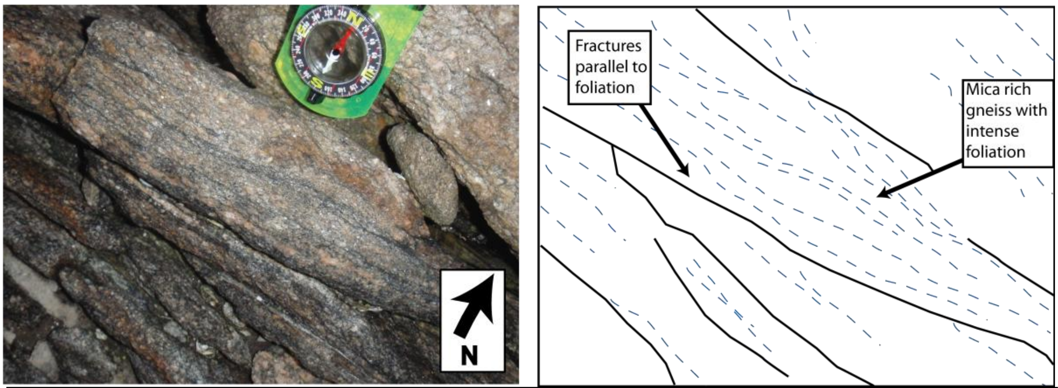


Figure 5.42 C. A close-up of the basement fabric within the shear zone at G1a. Basement fabric is strongly planar at small scales, and consists of alternately banded quartzofeldspathic and micaceous rocks. The planar nature of the bands, together with their contrasting mineralogies, makes these rocks ideal candidates for reactivation.

Figure 5.43 A. Continuous fractures at Guarujá, crosscutting basement fabrics and structures. Away from the larger shear zones this is the common mode of deformation at the outcrop, with fractures trending NNE-SSW, cutting the NE-SW basement

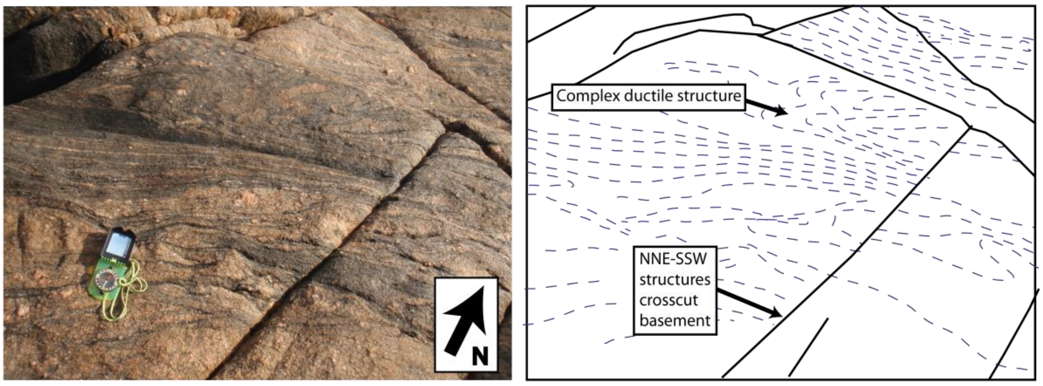


Figure 5.43 B. This figure illustrates some of the heterogeneity of the basement structures seen at Guarujá. Whiile towards the shear zones, the basement is strongly planar and micaceous, more felsic minerals, here seen as the pinkish bands, are present, weakly foliated and formed into complex folds. Whiile the basement here still trends NE-SW, it is crosscut by fractures of a number of orientations.

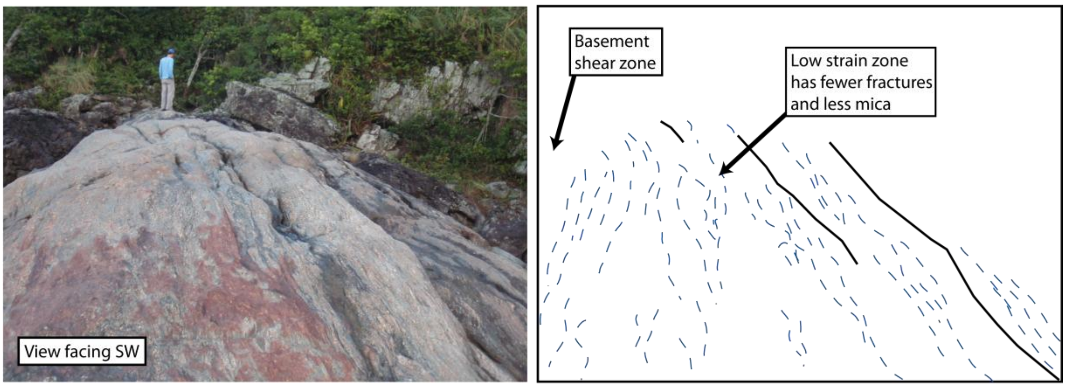
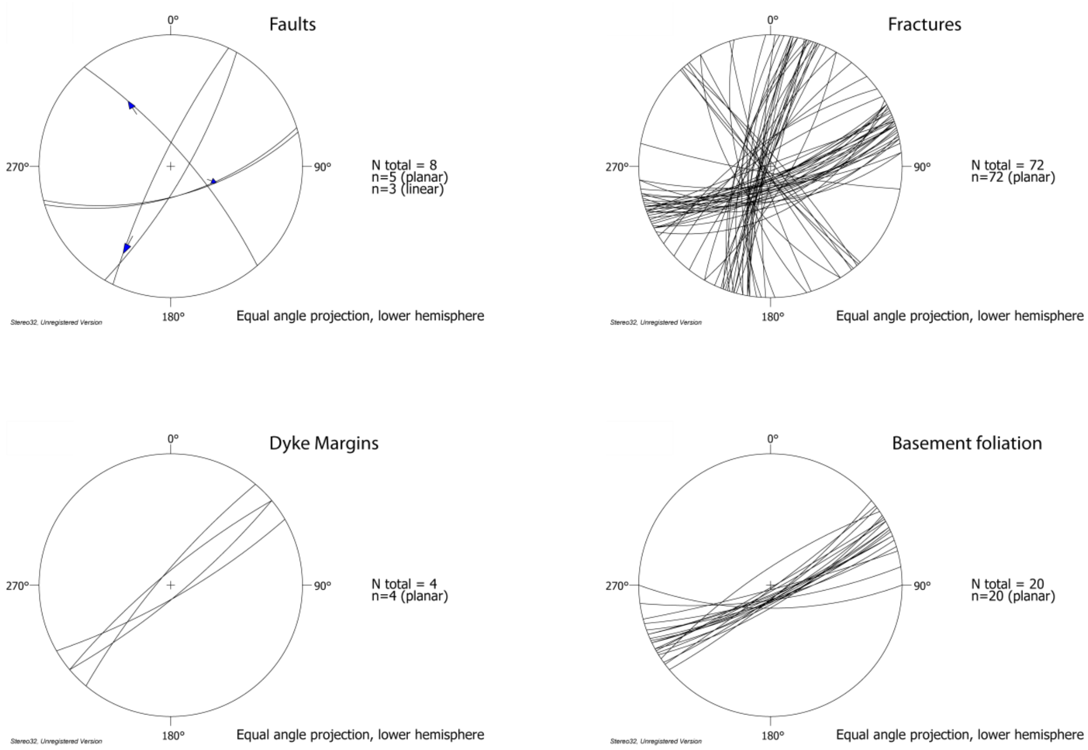


Figure 5.43 C. Between the shear zones at Guarujá, basement foliation is weaker, and structure is more complex. To the left and right of this photo are basement shear zones, where the majority of NE-SW fracturing is concentrated. Relatively few fractures in are found in the areas between the shear zones.



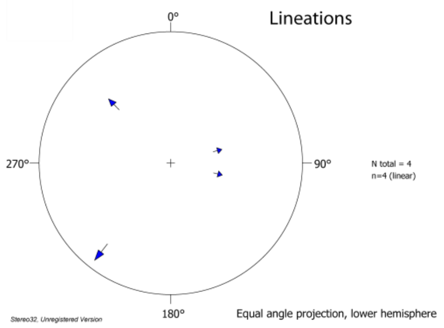


Figure 5.44. Stereonets of structural data collected at Guarujá. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.4.2 The Serra do Mar Domain - Discussion and Summary

Faults, fractures and dykes across the Serra do Mar region show dominantly NE-SW orientations (see individual outcrop stereonets). Faults and fractures of other orientations can, however, be seen at every outcrop, and the relationships between structures suggest mutually cross-cutting relationships. Dykes commonly show evidence of having intruded along pre-existing faults and fractures, implying that many brittle structures were present prior to the emplacement of the dykes. Faults in a NE-SW orientation commonly show sinistral kinematics. Basement is strongly heterogeneous in terms of both composition and orientation, and its relationship with later brittle structures is inconsistent, Some outcrops (e.g. Mambucaba) show good evidence for reactivation, whereas many others (eg. Praia das Conchas) show little or no evidence for basement influence of any kind.

There is a clear difference between the NE-SW orientation of the majority of structures observed in the Serra do Mar region, and the N-S orientation that would be predicted if the region had undergone E-W pure-shear extension. Many of the NE-SW faults display evidence for oblique slip in the form of moderately-plunging lineations on exposed fault surfaces, and in some cases, measurable oblique offsets (for example, the faults at Praia das Conchas).

In addition, if the assumption is made that the structures forming multiple fracture sets in the studied outcrops are the same age, it can be suggested that the region has deformed by a 3D strain, most likely transtension (De Paola et al., 2005a; De Paola et al., 2005b; Dewey et al., 1998). Faults and fractures forming Riedel shears were observed at multiple outcrops, and branching flower structures could be observed at some. Structures such as these are typical of transtensional deformation (Withjack and Jamison, 1986). The branches and jogs in some of the dyke margins also indicate that they intruded into an obliquely deforming region (e.g. Pollard, 1987 (Mccoss, 1986)), most likely during the early syn-rift given the 135-125Ma age of doleritic dykes on the margin.

No method exists in the literature to 'prove' transtension purely by analysing the geometric relationships between individual structures. Whilst previous studies (De Paola et al., 2005b; Wilson et al., 2006) have used paleo-stress methods to show that regions are consistent with having been deformed transtensionally, the data available in the Serra do Mar region - with limited evidence for offset of faults, and relatively few lineations are not sufficient for this type of analysis.

The McCoss construction (Mccoss, 1986) is a simple method to ascertain whether a region has undergone transtension, based on the angular relationship between regional σ3 (= Z axis of infinitesimal strain) and the margins of the deforming region. This method relies on either a knowledge of the regional extension direction, or the displacement vector of the boundaries of the deforming zone. It also relies on the boundaries of the deforming zone being known (Fig. 5.45). Assuming the boundaries of the deforming zone lie parallel to the main set of structures observed at each outcrop, and assuming a regional extension direction to lie E-W (based on the orientation of oceanic fracture zones), it is possible to test in which outcrops the deformation should be transtensional. The results are summarised in the table below.

Outcrop name	Structures measured	main trend of structures	extension direction	Angle A	TT?	Field of transtension - McCoss (1986)
Praia das Focas	Faults	109	090	109	Yes	General Wrench
	Fractures	069	090	111	Yes	General Extension
Praia Das Conchas	Faults	066	090	114	Yes	General Extension
	Fractures	068	090	112	Yes	General Extension
Quatis	Faults	038	090	142	Yes	General Extension
	Fractures	N\A	090	N\A	N/A	N/A
Caraguatatuba	Faults	N\A	090	N\A	N/A	N/A
	Fractures	067	090	113	Yes	General Extension
São Sebastião	Faults	043	090	137	Yes	General Extension
	Fractures	064	090	116	Yes	General Extension
Ponta Negra	Faults	036	090	144	Yes	General Extension
	Fractures	051	090	129	Yes	General Extension
Grumari	Faults	115	090	115	Yes	General Extension
	Fractures	114	090	114	Yes	General Extension
Mambucaba	Faults	032	090	148	Yes	General Extension
	Fractures	027	090	153	Yes	General Extension
Ubatuba - Ponta Grossa	Faults	046	090	134	Yes	General Extension
	Fractures	060	090	120	Yes	General Extension
Ubatuba - Praia Sununga	Faults	042	090	138	Yes	General Extension
	Fractures	043	090	137	Yes	General Extension
Ubatuba - Praia Fortaleza	Faults	055	090	125	Yes	General Extension
	Fractures	056	090	124	Yes	General Extension
Guarujá	Faults	074	090	106	Yes	General Wrench
	Fractures	072	090	108	Yes	General Wrench

Table 5.2: Outcrops in the Serra do Mar region, assessed using the McCoss method (McCoss, 1986), for transtensional (TT) origin and the field of transtension under which these structures may have formed. All of the outcrops are transtensional, and a number (highlighted red in the 'Angle A' column) are considered wrench-dominated (A < 109°). A number of others (highlighted green) are within 16 degrees of being considered wrench dominated (109°>A<125°).

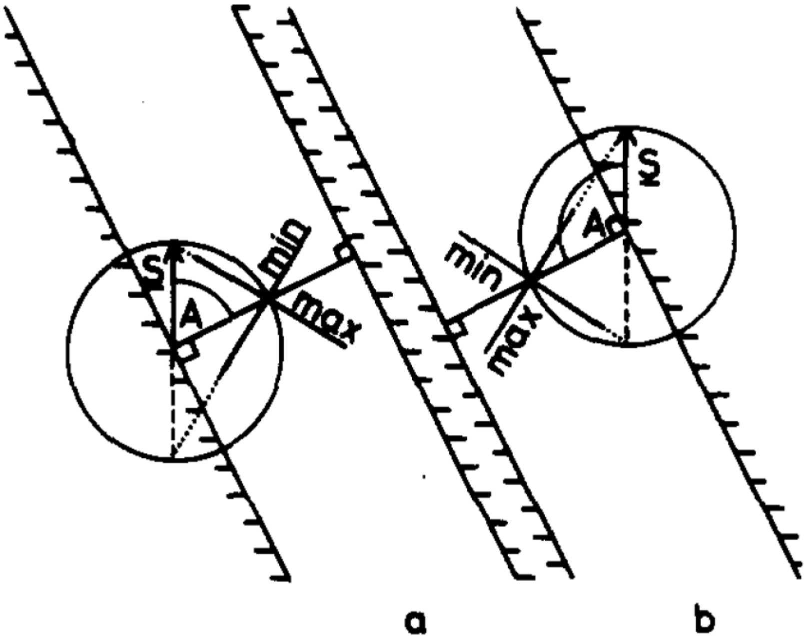


Figure 5.45. The McCoss construction for a) transpression, where A is the angle between compression (S) and the normal to the deforming zone; and b) transtension, where A is the angle between the extension direction (s) and the normal to the deforming zone. Using this method, the orientation of the axes of the infinitesimal strain ellipse can also be ascertained (min and max)

Field data from outcrops across the Serra do Mar show a clear dominance in NE-SW trends for fault- and dyke-related structures. The parallels between these structures and the map view geometry of basement structures are unlikely to be coincidental, although in outcrop, with some notable exceptions (Guarujá and Mambucaba) basement fabrics typically dip too shallowly, or is too structurally complex to show obvious direct reactivation. The dominant structural trend, observed in lineament analysis and field data is NE-SW, but, secondary trends show significant variations across the Serra do Mar region, from N-S at outcrops such as Praia das Conchas and Guarujá, to NW-SE at Mambucaba and Ponta Grossa, and NNE-SSW in the Ubatuba region. This variation is most likely to be due to variations in local stresses during the deformation of the region, possibly reflecting strain partitioning during transtension. This conclusion is based on the absence of clear evidence for these secondary trends being controlled by basement structures or features.

Structural variations due to strain partitioning are likely over such a large area, if the region has been deformed transtensionally, because strain compatibility between deforming areas becomes less likely over larger regions (De Paola et al., 2005b). Secondary trends are often consistent with E-W extension, such as NW-SE dextral structures observed at Praia das Conchas, for example. Other outcrops, such as Guarujá, Mambucaba also show steeply dipping fractures trending NNE-SSW, closer to orthogonal to regional extension (normal faults in a N-S would be expected in an extensional setting). As seen at outcrops such as Praia Sununga and Praia das Focas, both primary and secondary trends may also be related to later tectonic events, as some evidence for structures cutting the dykes can be observed

There is little direct evidence for reactivation at most of the outcrops studied. Since it is unlikely to be coincidental that the main trends at all outcrops (with the exceptions of Praia das Focas and Ponta Negra) are parallel to regional scale basement structures, it is reasonable to suggest that some other larger scale structures such as regional scale shear zones or mantle fabrics, formed during the Brasiliano orogeny, may be responsible for the geometries observed. The outcrop at Quatis could be considered an example of the reactivation of a large shear zone, and other published evidence for similar structures supports this view (Gontijo-Pascutti et al., 2010). Other studies provide evidence which shows preferentially aligned mantle fabrics that could have been reactivated during rifting (Assumpcao et al., 2006). In these scenarios, smaller-scale reactivation of foliations such as that observed at Mambucaba would only be observed where the basement fabric is preferentially aligned to be reactivated. If reactivation of large-scale structures or mantle fabrics was the sole control on the orientation of rift related structures, one can question whether structures found between the regions where reactivation is the dominant control on brittle faulting would still trend parallel to the reactivated structures and fault obliquely. The alternative is that brittle structures, which are not basement-controlled, would trend at a higher angle to regional extension, accommodating the dip-slip element of rifting, while the basement influenced structures accommodate the strike slip component of rifting. An example of this can be seen at Guarujá, where faults which reactivated basement structures trend NE-SW, whereas structures formed between these reactivated structures trend closer to N-S.

A model involving dip-slip structures accommodating E-W extension, while basement structures reactivate as strike-slip or oblique-slip faults fits well with other models of transtension (McClay et al., 2002), but does not reflect what we actually see on the onshore margin. The dominant trend of brittle structures and dykes at all outcrops (with the exception of Praia das Focas) is NE-SW, regardless of basement structure, not orthogonal (N-S) to the rifting direction, as would be predicted by McClay et al. (2002), amongst others. A possible reason for this discrepancy may be the dykes, which intruded during the early rift, which we see preferentially intruding along NE-SW structures. Since dykes commonly intrude perpendicular to the minimum principal stress axis, this could possibly be interpreted as the region initially having extended orthogonally in NW-SE extension, before later rifting in an E-

W direction. However, the kinematics of faults and fractures around the dykes, which are consistently oblique and sinistral do not support an initial NW-SE oriented extension. Whether the dykes opened obliquely is also important to consider. My evidence shows that whilst dykes show structures consistent with having intruded into an obliquely deforming region, they typically do not show strike-slip offsets across their margins.

Structures observed crosscutting the dykes are oriented closer to N-S than those that do not cut the dykes (these structures can be seen at Praia das Conchas and at Mambucaba), suggesting that brittle structures formed more orthogonally to regional extension at some point following the intrusion of the dykes (i.e. deformation became more extension-dominated). NE-SW trending dykes will not have accommodated much of the E-W extension under N-S rifting, if they have opened purely orthogonally, Therefore it seems reasonable that the E-W component of extension must have been accommodated by oblique deformation on the faults and fractures. This model is similar to the model presented by Teyssier and Tikoff (1999), in which the faults and fractures deform more obliquely in response to the addition of material; in this case, the dykes. Under this model, following the intrusion of the dykes, faults and fractures would no longer be able to deform at such low angles to regional extension. See Chapter 7 for further discussion.

While the model of dyke-influenced rifting described above seems appropriate for the Serra do Mar region, it does not explain how the small scale structures such as the fractures and dykes came to form in their predominant NE-SW orientations, especially since the fractures appear to have formed prior to the intrusion of the dykes. The model also does not account for the behaviour of the margin as a whole, as it only applies to one arm of the apparent triple junction suggested by the lineament study (see sections below).

5.5 The Ponta Grossa Dyke Swarm

Only three main localities from this region were studied, due to the fact that much of the coastline consists either of coastal marshland or several hundred kilometre long beaches. The outcrops studied are from the Ilha do Mel, Guaratuba, and Ilha do São Francisco. All dykes studied in these regions are thought to be related to the development of the Ponta Grossa dyke swarm at approximately 135Ma. The basement in this region is still part of the Ribeira belt and broadly trends NE-SW. The dykes and many of the faults and fractures in this region trend NW-SE.

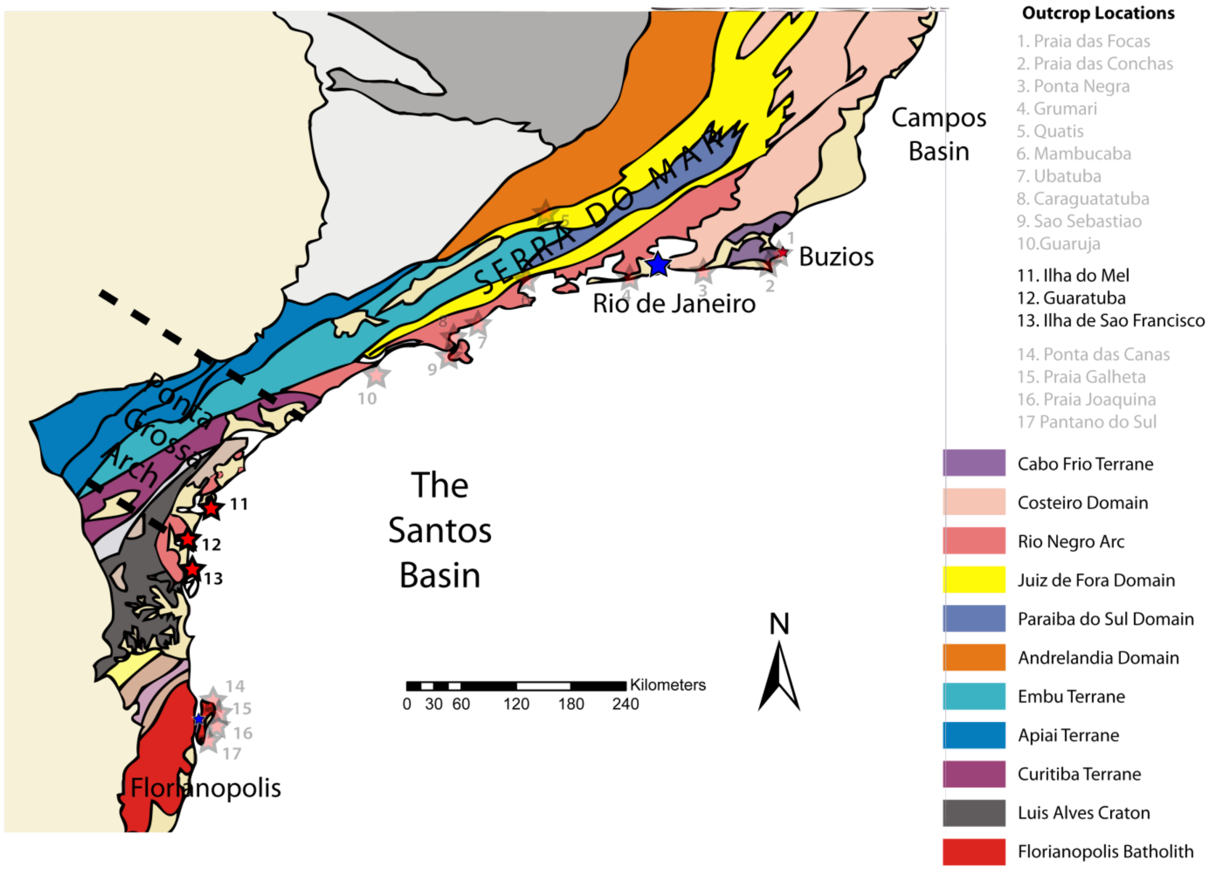
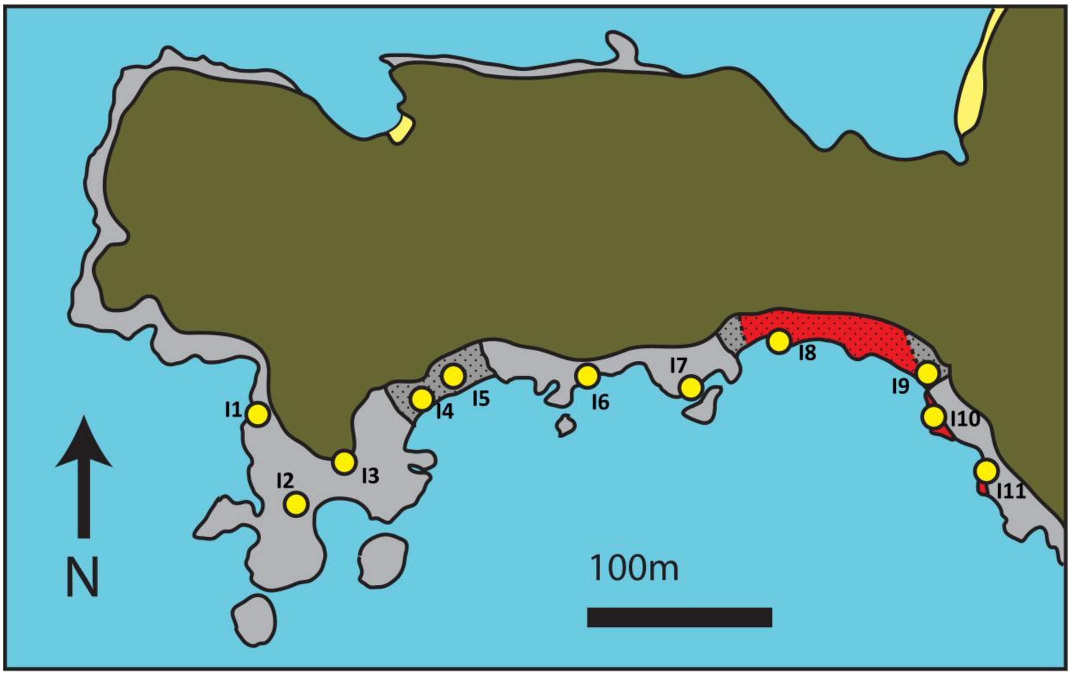


Figure 5.46 – Terrane map of the study area, after Passarelli et al. (2011), showing the locations of studied outcrops. Numbers 11-13 (highlighted) are the outcrops in the Ponta Grossa domain, and are situated in the Rio Negro Arc Terrane, in the region of the Luis Alves Craton in the West of the onshore study area.

5.5.1.1 Ilha Do Mel



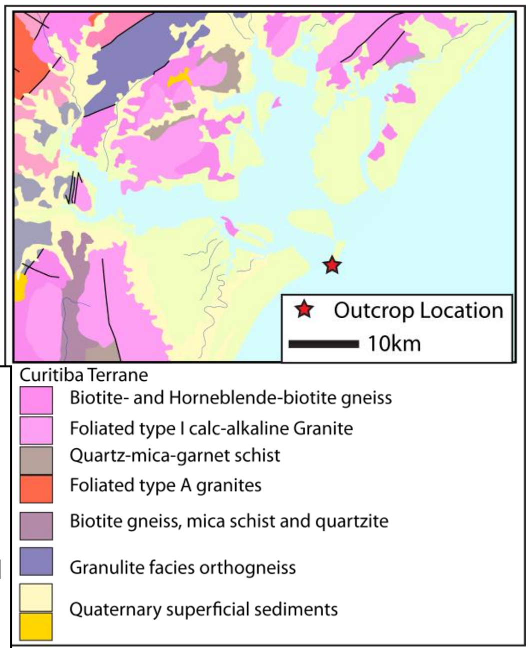


Figure 5.47 A. simplified map of the outcrop at Ilha do Mel, showing waypoints visited. The dyke is highlighted in red, and basement in grey. Rubble is represented by black dots. B. Google earth aerial photograph of the outcrop region, showing the locations of outcrops visited (yellow circles). B. geological map of the area, showing key basement lithologies and structures (black lines)

Outcrop description

This outcrop is exposed along a stretch of coast over several hundred metres (Fig. 5.47C). The basement rocks consist of Paleoproterozoic migmatitic gneisses of the Curitiba terrane (Fig. 5.47B) (chapter 2.3.1.1.1). The basement is intensely faulted and fractured, and intruded by a large NE-SW trending doleritic (and therefore syn-rift) dyke towards the east of the outcrop (Fig. 5.47A).

Outcrop-scale structures

Basement foliation is relatively planar at this outcrop, trending NE-SW, and dipping shallowly. Only one dyke margin is exposed (Fig. 5.49C), so its relationship with fractures is relatively unclear, although it appears to trend NW-SE, parallel to a large number of fractures at this outcrop. It is doleritic in composition and dykes on the island of similar composition have been dated at 120Ma (Peate, 1997). Three sets of fractures cut the dyke, and contain 1-2mm of fine grained red/brown coloured gouge (Figs 5.49A, B, C). One of the dyke margins is obscured beneath blocks of rubble. Where seen, the eastern margin of the dyke appears to show a primary igneous contact with basement, and it does not appear to have been directly controlled by fractures.

Three sets of faults and fractures were observed which trend ENE-SSW, WNW-ESE, or NNW-SSE (Fig. 5.50), consistent with lineament trends in the area, and the trend of the dyke margins, as observed. Where observed, offsets on WNW-SSE and NNW-SSE trending faults are dextral. The ENE-SSW set trends approximately perpendicular to the dyke margins (see below). The NNE-SSW and NNW-SSE sets show strike-slip lineations. Some small NNW-SSE trending fractures contain 1-5mm of black crystalline material (possibly tourmaline). Fractures containing this material also contain clasts of quartz vein material (Fig. 5.48A). Fractures containing this black material show apparent normal offsets of basement foliation, although shallowly plunging slickenlines can be identified on other fault surfaces.

Some NE-SW trending fractures lie parallel to basement fabrics, but the majority of faults and fractures dip steeply and cut across relatively the shallowly dipping basement structures (Fig. 5.48C). The fractures both near and away from the dyke form complex sets, in which cross-cutting relationships are inconsistent, and sometimes mutual cross-cutting relationships are observed (Fig. 5.48B). The fractures cutting the dyke are oriented parallel to the some of the other main sets of fractures, but the dominant trend is NNE-SSW, as opposed to the NNW-SSE trend observed away from the dyke.

Interpretation

This outcrop shows complex structures that reflect the lineament trends in the Ponta Grossa lineament zone well. Much of this complexity may be due to the interplay between the NW-SE trending dykes, and the NE-SW trending basement fabrics, although only a few reactivated structures are found here due to the relatively shallow dip of the basement structures on the island. The limited number of fractures which can be seen to reactivate basement fabrics suggests that, unless these fractures have very large offsets, basement reactivation is unlikely to be the dominant control on the orientation of structures at this outcrop. Dextral offsets on some NNW-SSE faults, together with shallowly-plunging lineations on fault surfaces suggest an oblique element to the deformation in this area.

The dyke at Ilha do Mel trends NW-SE, consistent with the main swarm. The 120Ma age of other dykes on the island is, while syn-rift, is younger than dates proposed for the Paraná volcanic province that they are thought to feed (Peate, 1997). Significant numbers of NNE-SSW trending fractures within the dyke indicate a post-rift event. The orientation of the post-dyke fractures is consistent with post-dyke fractures seen at other outcrops such as Praia das Conchas. The black fracture infill seen away from the dyke, together with the quartz veins, indicates a hydrothermal event that has happened after the formation of the basement fabrics. Fractures containing black material (interpreted as tourmaline at outcrop) and quartz veins trend parallel to many of the other fractures at the outcrop. This parallelism could be coincidental, or could suggest that the fracturing event at this outcrop was part of a local or regional hydrothermal event.

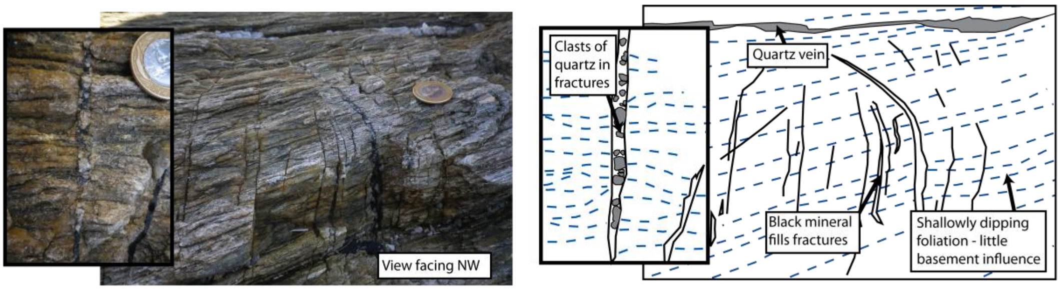


Figure 5.48 A. Vein material (Tourmaline) in fractures on Ilha do Mel. The material is black and slightly foliated in appearance. No evidence of these fractures cutting the quartz vein can be found, and the presence of clasts of quartz within them indicates that they are unlikely to have formed before the veining event. Some of these fractures appear to accommodate dip-slip offsets (see inset), and they trend roughly parallel to other, non mineralized fractures at the same outcrop.

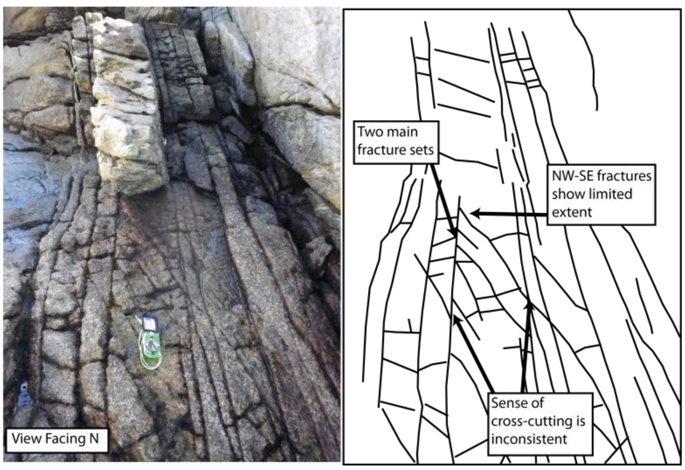


Figure 5.48B. Multiple sets of fractures with different orientation are common at Ilha do Mel. Establishing whether one set consistently crosscuts another is difficult, as fractures within a set appear to cut the other set inconsistently. This may be due to the NW-SE set forming later, or both sets forming at the same time.

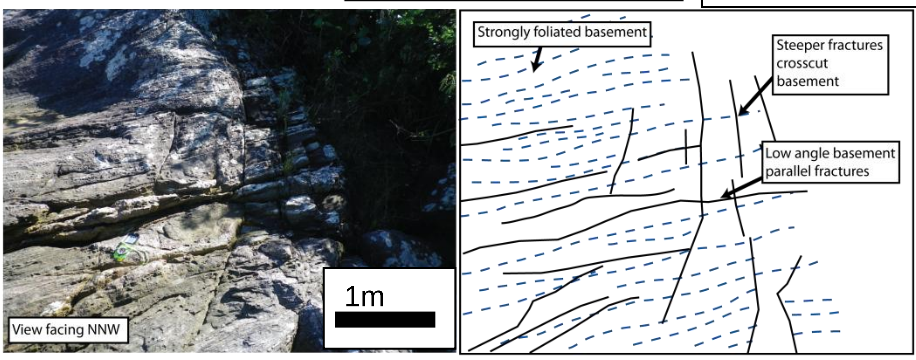


Figure 5.48 C. Some lower angle fractures reactivate the shallowly dipping basement. Some steeper dipping fractures crosscut basement fabrics. At Ilha do Mel, the dip and strike of the basement is relatively constant, though similarly to at Guarujá, it is locally vary variable. While the majority of basement trends NE-SW, parallel to the Ribeira belt, fractures do not commonly reactivate it, highlighting the apparent lack of basement influence on the Ponta Grossa dyke swarm.

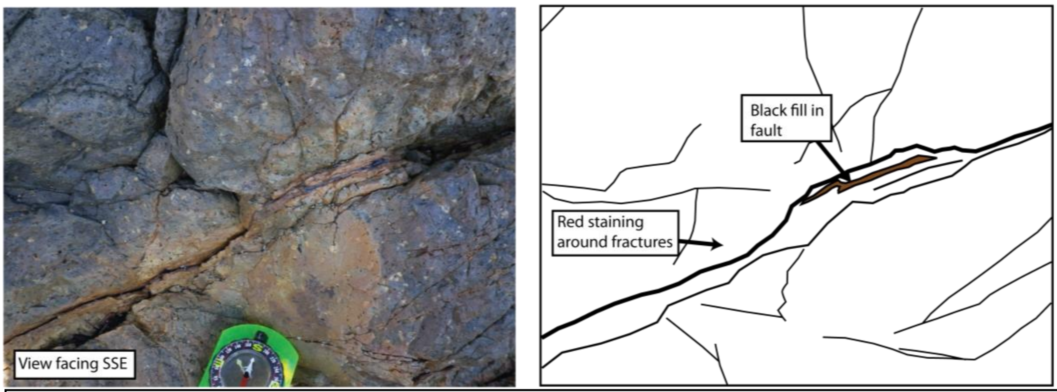


Figure 5.49 A. Fractures within the dyke at Ilha do Mel are commonly stained red, and in some cases show black and brown fault rock. The dyke is doleritic in composition, with 2-3mm plagioclase phenocrysts. The red staining could result from the weathering of the dyke by meteoric water, though it does appear to be confined to the fractures, and fracture surfaces. Lineations on these fractures suggest strike-slip kinematics.

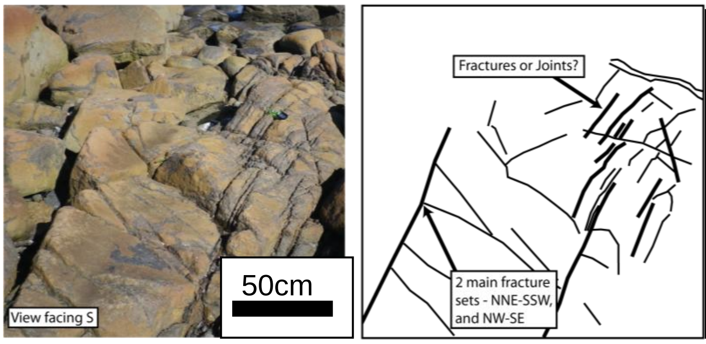


Figure 5.49 B. Two main sets of fractures cut the dyke at Ilha do Mel. Some of these may be joints formed during cooling, as the NNE-SSW set is approximately perpendicular to its margins.

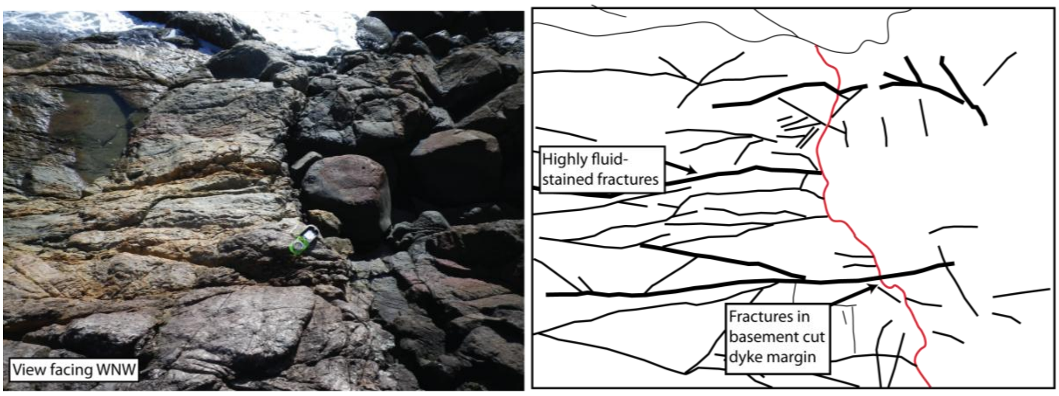


Figure 5.49 C. Red stained fractures from the country rock at Ilha do Mel can be seen continuing into the dyke. The dyke at this outcrop is not well exposed, with much of its outcrop covered by rubble.

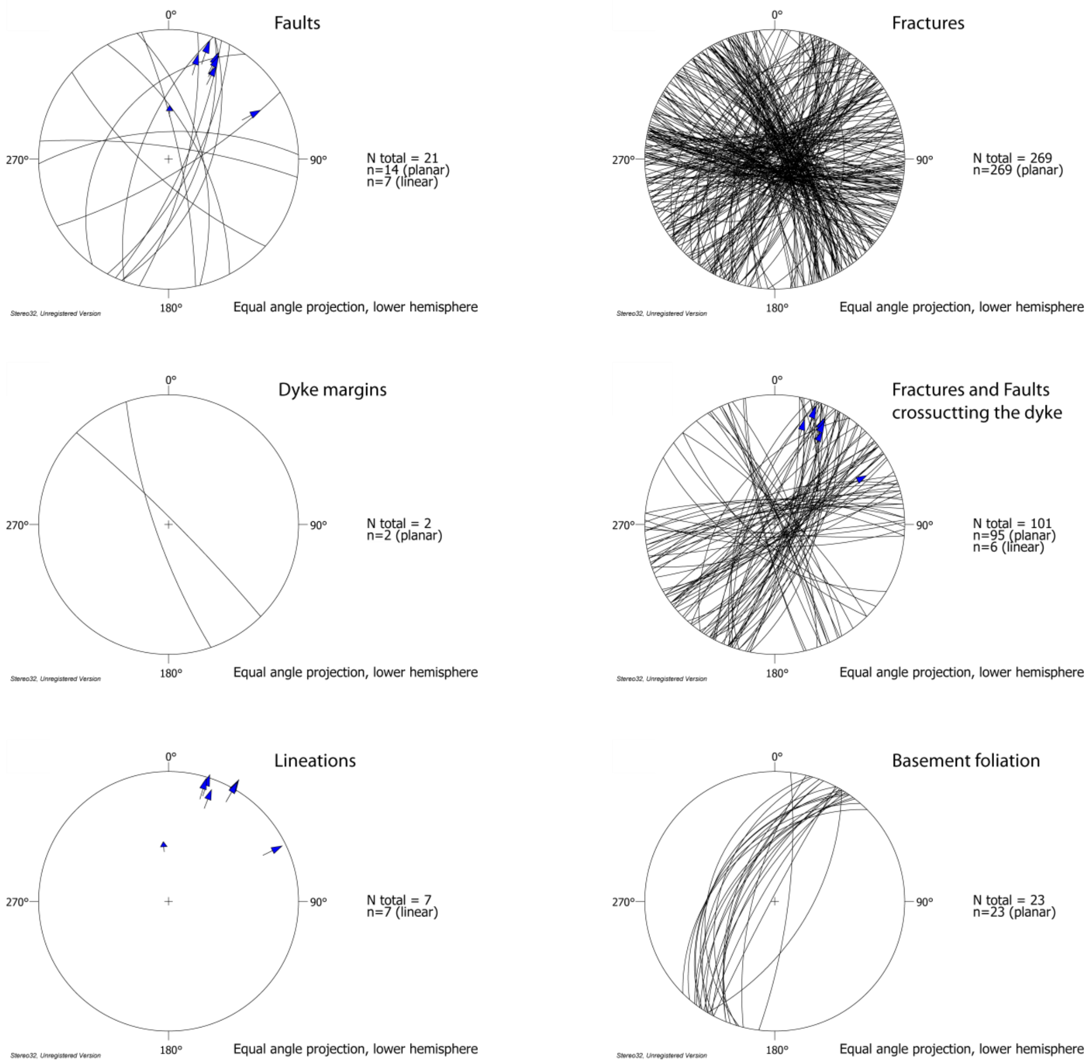


Figure 5.50. Stereonets of structural data collected on Ilha do Mel. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.5.1.2 Guaratuba

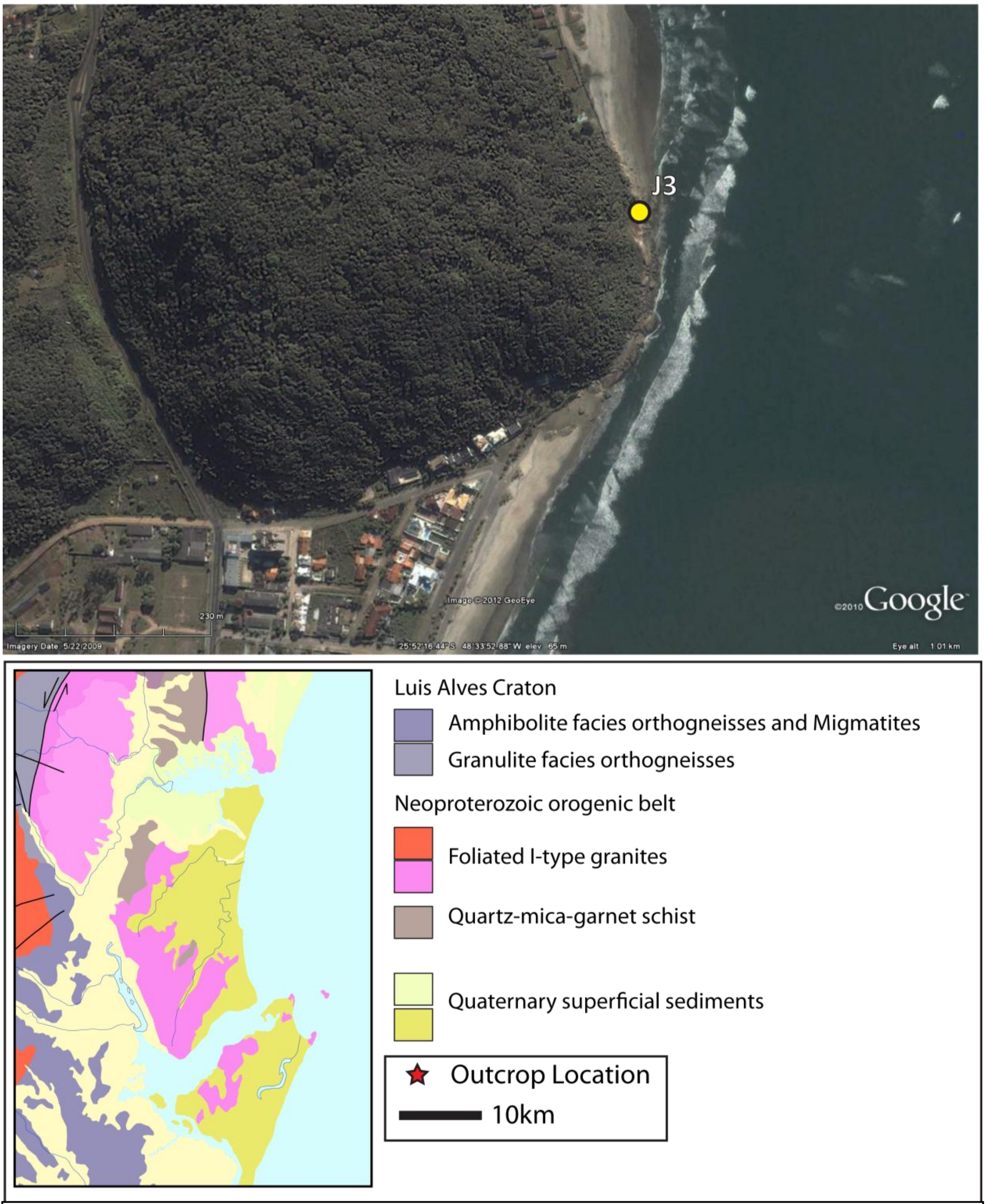


Figure 5.51 A. Google earth aerial photograph of the outcrop region at Guaratuba, showing the regional terrain, and the location of the outcrop (yellow circle). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

The outcrop at Guaratuba is found on the northern side of a headland, to the north of the town of Guaratuba (Fig. 5.51A). The exposure is mostly flat, and covers an area of about 20m^2. This outcrop comprises gneissose basement of Neoproterozoic age, crosscut by multiple generations of pegmatites, intruded by a NW-SE trending dolerite (syn-rift) dyke, and cut by faults and fractures. Basement rocks at this outcrop belong to the Curitiba terrane (chapter 2.3.1.1.1), and are found close to the boundary between the Ribeira belt and the Luis Alves craton (Fig. 5.51B).

Outcrop-scale structures

The basement here is highly complex, with multiple generations of intrusion of pegmatites. The degree of foliation varies strongly throughout the outcrop with the dyke intruded into weakly foliated granitic gneiss.

A large (5m width) dyke trends NW-SE consistent with the trend of the Ponta Grossa dyke swarm. The margins are not straight and 10-50cm wide offshoots are present trending NNW-SSE, apparently intruding along pre-existing faults, some of which show 10cm+ reverse offsets (Fig. 5.52A). One dyke offshoot shows irregular margins, and apparently intrudes along a basement pegmatite vein, and differs in character from the offshoots which intrude along faults and fractures, which are straight sided.

The faults observed here trend NNW-SSE, parallel to the offshoots from the dyke margins (Fig. 5.53). One lineation, suggesting strike-slip kinematics was measured, plunging shallowly to the NW. Some of the NNW-SSE-striking faults show reverse offsets, similarly to those structures that have been intruded by dyke offshoots. Two main sets of fractures were observed, one trending parallel to the faults, which is the set most commonly reactivated by the small dykes, and another trending ENE-WSW (Fig. 5.53), which shows no relationship with faults or dykes, but strikes sub-parallel to some of the basement foliation trends.

Interpretation

The relationship between the dyke and pre-existing fractures is clear at this outcrop, with some structures that dykes have intruded along showing reverse offsets. Unusually, the main dyke does not appear to be influenced by pre-existing brittle structures whereas the dyke offshoots do (Fig. 5.52C). This could be because the main dyke is influenced by a larger feature not visible at this outcrop (such as a basement structure or a larger rift-related fault). While no basement influence on the fractures can be observed, due to the weakly foliated, complexly deformed basement, one of the dyke-offshoots does travel along a pegmatite. Its morphology is significantly affected by this, and it appears wispy and braided, as opposed to straight sided, unlike those dykes which intrude along fractures.

Faults here typically have a relatively large offset (up to 50cm at Guaratuba, compared to less than 1cm at the majority of other outcrops) when compared with those at other outcrops. Senses of offset on some faults are also atypical of other outcrops across the region, with some faults displaying reverse offsets. Where dykes intrude along faults, the offsets observed across the faults may be interpreted to be the result of faulting, not dyking. This is because similar offset amounts can be observed on faults which have not been intruded by dykes. Offsets across parallel dykes (5.50B) can be inconsistent when viewed from above, suggesting oblique offset, with both a dip-slip, and a strike-slip element.

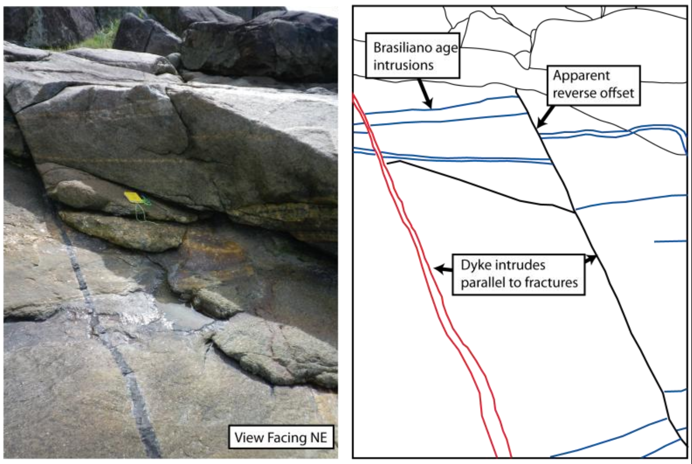


Figure 5.52A. A small dyke at Guaratuba, branched from the main dyke, parallel to an apparently reverse-offset fracture. Basement foliation here is relatively shallowly dipping, and cut by a number of generations of intrusions, the Dolerite dyke being the youngest. The fractures appear to predate the dyke, as it closely follows their geometry.

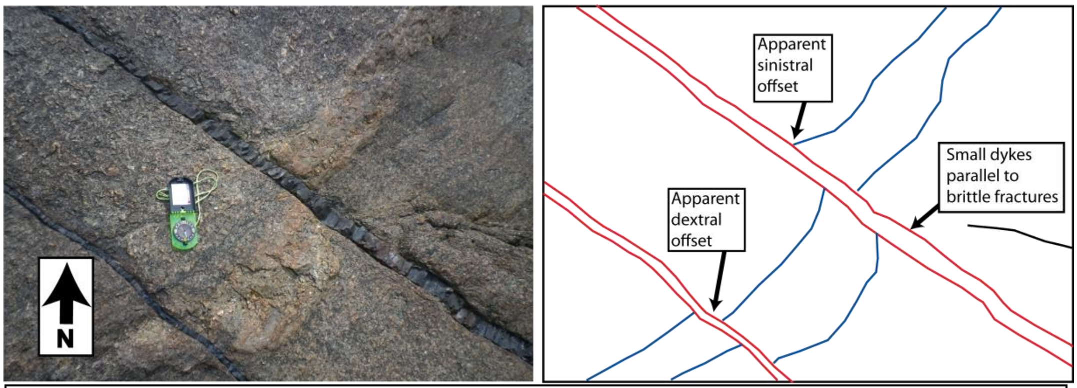


Figure 5.52B. These two small dykes cut a Brasiliano age (or older) intrusion at Guaratuba. These narrow dykes are seen to branch from the main dyke, parallel to fractures. It is difficult to tell whether these offsets are accommodated across the dykes, or were formed by the faults the dykes intrude along.

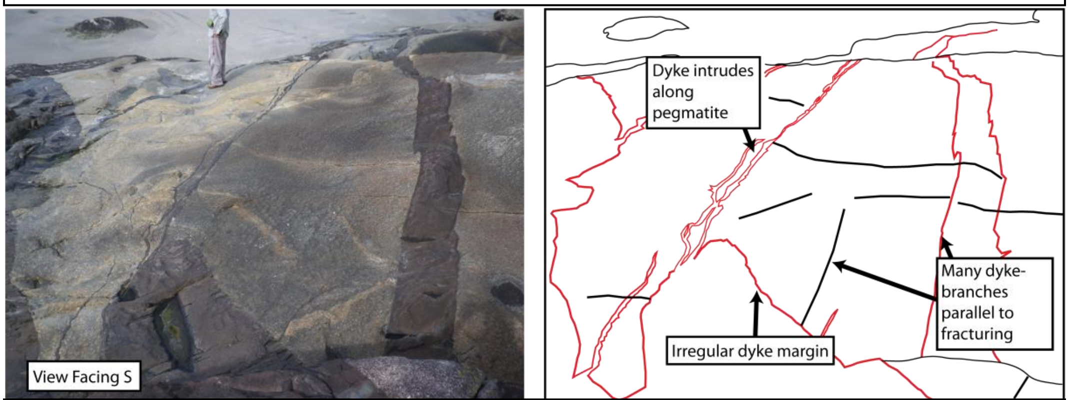


Figure 5.52C. A number of branches from the main dyke at Guaratuba (at the base of the image), parallel to many basement fractures. The irregular margin of the main dyke suggests it was not intruded along pre-existing fractures, whereas the straighter branches appear to be controlled by pre-existing fractures and basement features

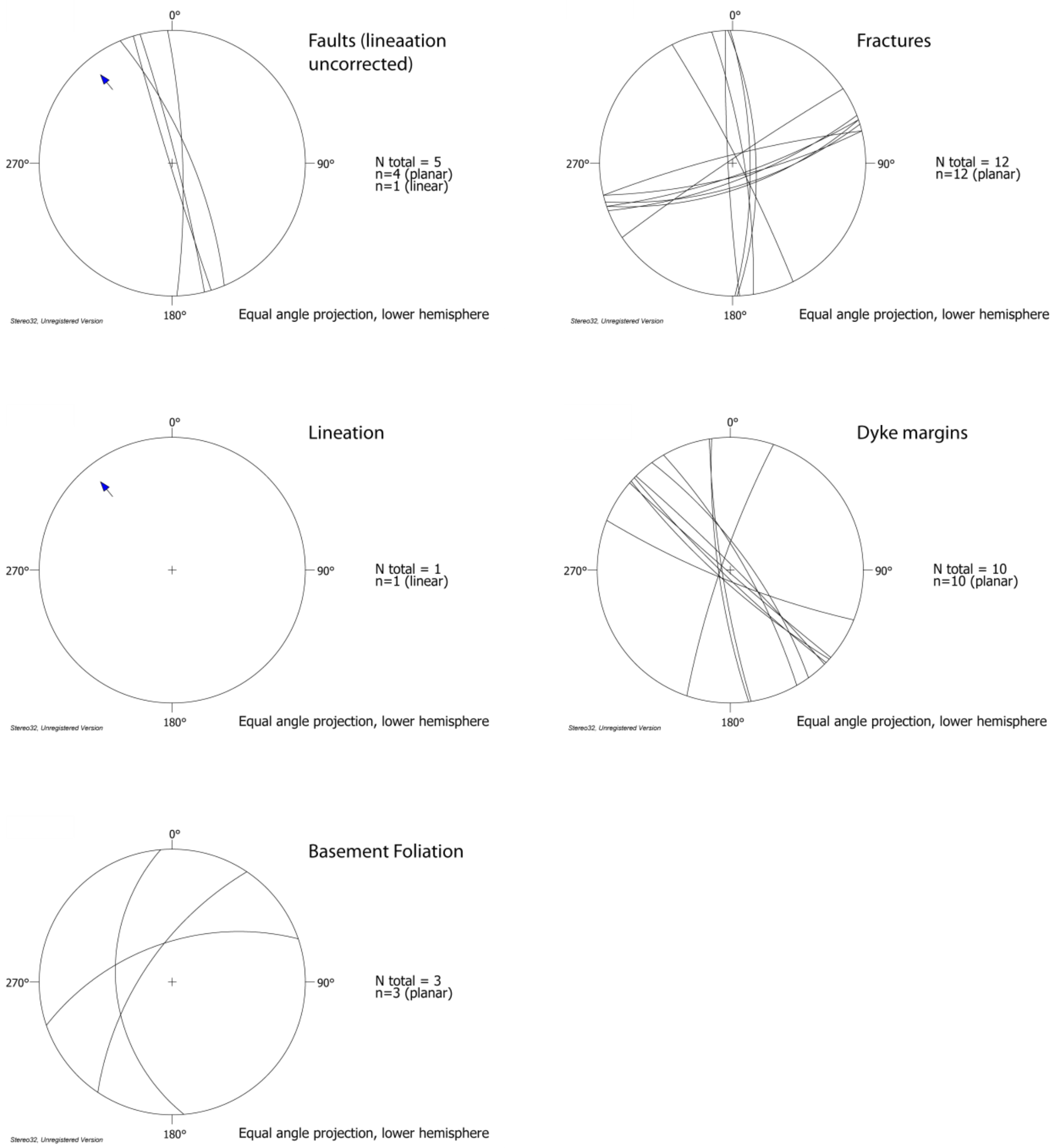


Figure 5.53. Stereonets of structural data collected at Guaratuba. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.5.2 Ilha de São Francisco, SC

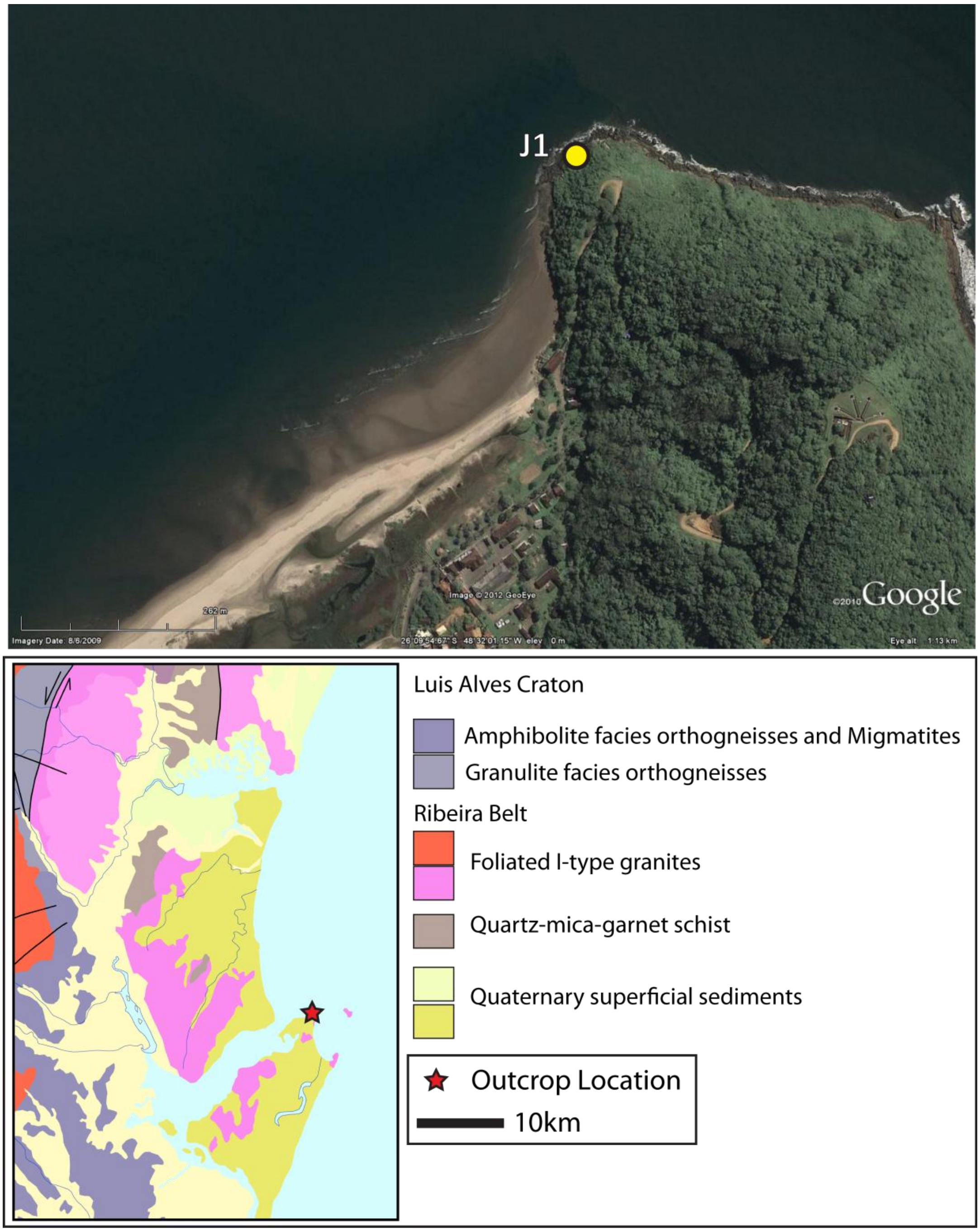


Figure 5.54 A. Google earth aerial photograph of the outcrop region at Ilha do Sao Francisco, showing the regional terrain, and the location of the outcrop (yellow circle). B. geological map of the area, showing key basement lithologies and structures (black lines).

Outcrop Description

The outcrop on Ilha de Sao Francisco can be seen to the east of a beach on the northern tip of the island. A strip of rock 10m wide and 40m long is exposed between the sea and a steep forested slope (Fig. 5.54A). This outcrop is found between two lineament zones - the Ponta Grossa domain and the Florianopolis domain. The outcrop consists of a dolerite dyke intruding weakly foliated granitic gneiss of the Neoproterozoic Curitiba terrane (chapter 2.3.1.1.1), close to the Luis Alves Craton (chapter 2.3.1.2) (Fig. 5.54B).

Outcrop-scale structures

The basement here is strongly foliated, and trends roughly NNW-SSE, dipping shallowly to the NW. The basement is cut by a 10m wide, NW-SE trending dyke (Figs 5.55A,B,C). The margins of the dyke display an intrusive contact with basement, and do not appear to be influenced by faults or fractures (Fig. 5.55C).

Only one fault was observed on the island, with a moderately to steeply-plunging lineation. The fault trends NE-SW, and cuts the NW-SE trending dyke, and runs broadly parallel to a number of other NE-SW trending fractures, also cutting the dyke. Fractures at this outcrop trend in a variety of orientations, but the dominant trends observed are NE-SW. Most fractures dip steeply (Fig. 5.56). Many fractures which do not appear to cut the dyke also trend NE-SW (they are truncated at the dyke margin). Many NE-SW trending fractures display sinistral Riedel shear geometries (Fig. 5.55B). Other than these Riedel shears, there is little evidence for kinematics on any of the fractures at this outcrop, and those that can be observed cross-cutting the dyke margin do not appear to offset it. A small number (<10) of NW-SE fractures are also observed, some of which crosscut the dyke.

Interpretation

The dyke on this small island may form either a part of the Ponta Grossa swarm, or the Florianopolis swarm. The NW-SE trend of the dyke and many fractures is also consistent with outcrops in the Ponta Grossa swarm. The shallow dip of the basement fabric does not favour reactivation by steeply-dipping faults, neither does the weak foliation. Whilst it trends parallel to fractures, the irregular contact between the dyke and basement (as opposed to straight, well defined contacts such as that observed at Praia das Conchas, for example) suggests that it may not have intruded along pre-existing fractures. Despite this, the dyke does trend parallel to other dykes in the Ponta Grossa swarm, which suggests it may have been influenced by similar processes.

In a regional context, this outcrop possibly shows the southern extent of the Ponta Grossa Domain as it is located to the far south of the Ponta Grossa Lineament zone The outcrop also shows the extent of some of the post-dyke deformation, given the large number of faults which cut the dyke. There is no basement reactivation observed here, although a large number of structures trend NE-SW, consistently with other outcrops in the Ribeira belt where the basement is not well aligned for reactivation.

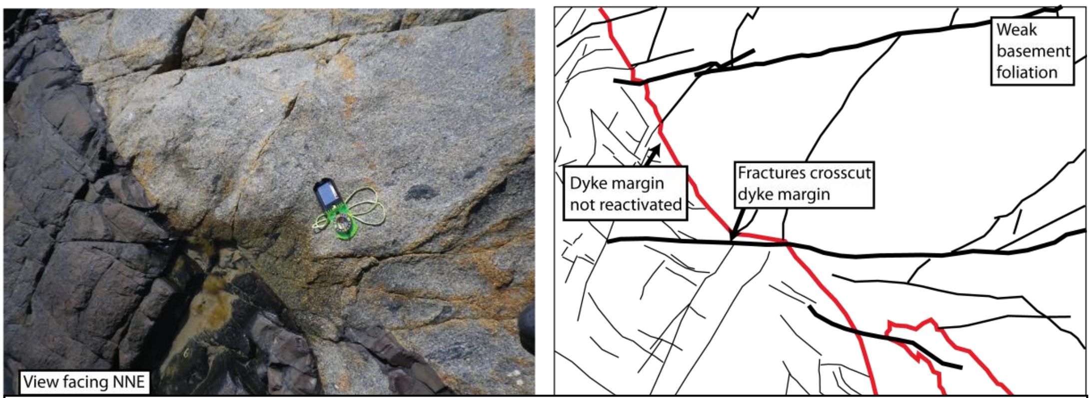


Figure 5.55A. A small number of fractures can be observed crosscutting the dyke margin at Ilha do Sao Francisco. The margin itself still shows a primary intrusive contact with the basement, showing that whilst there was a later event cutting the dyke, it did not reactivate the dyke magin.

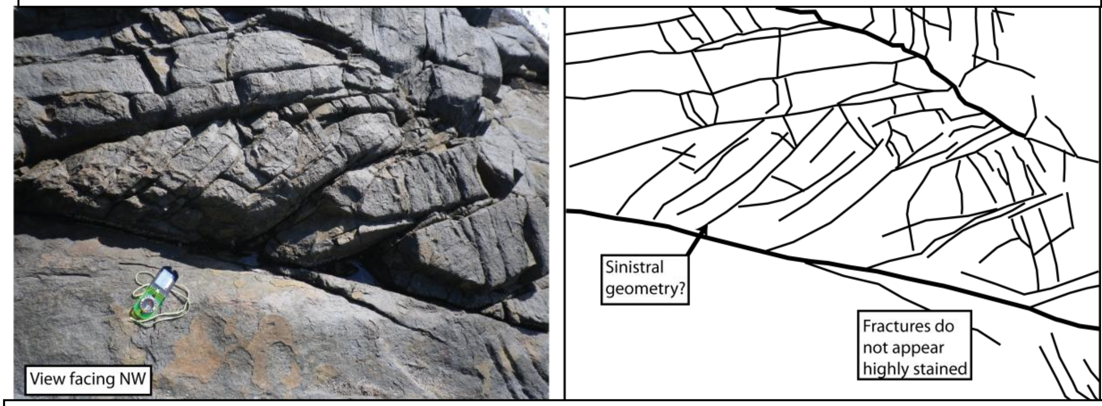


Figure 5.55B. Many fractures can be seen within the dyke, forming sinistral geometries such as these NE-SW trending structures. Whilst this is consistent with regional E-W extension, and transtension in the Ribeira belt, these structures are clearly younger than the earliest syn-rift (135Ma).

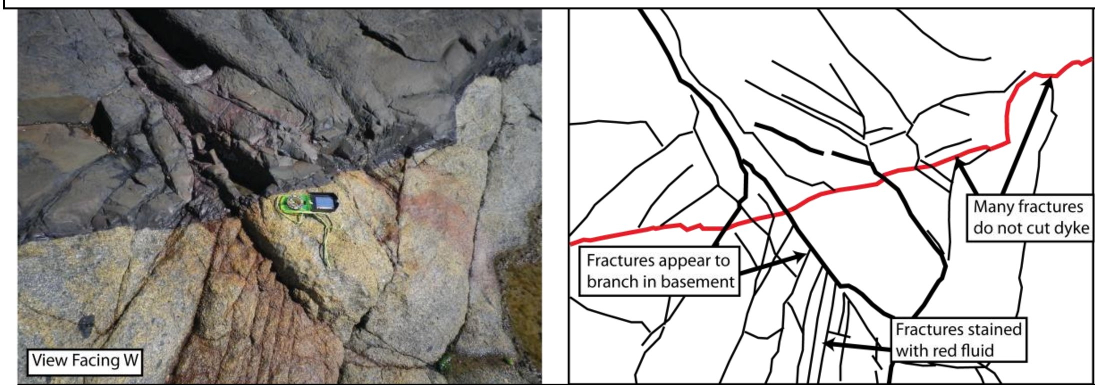


Figure 5.55A. Many of the structures which cut the dyke on Ilha do Sao Francisco show red staining, both within and outside the dyke. The structures branch, consistently with oblique deformation. Many structures with similar orientations do not cut the dyke margins.

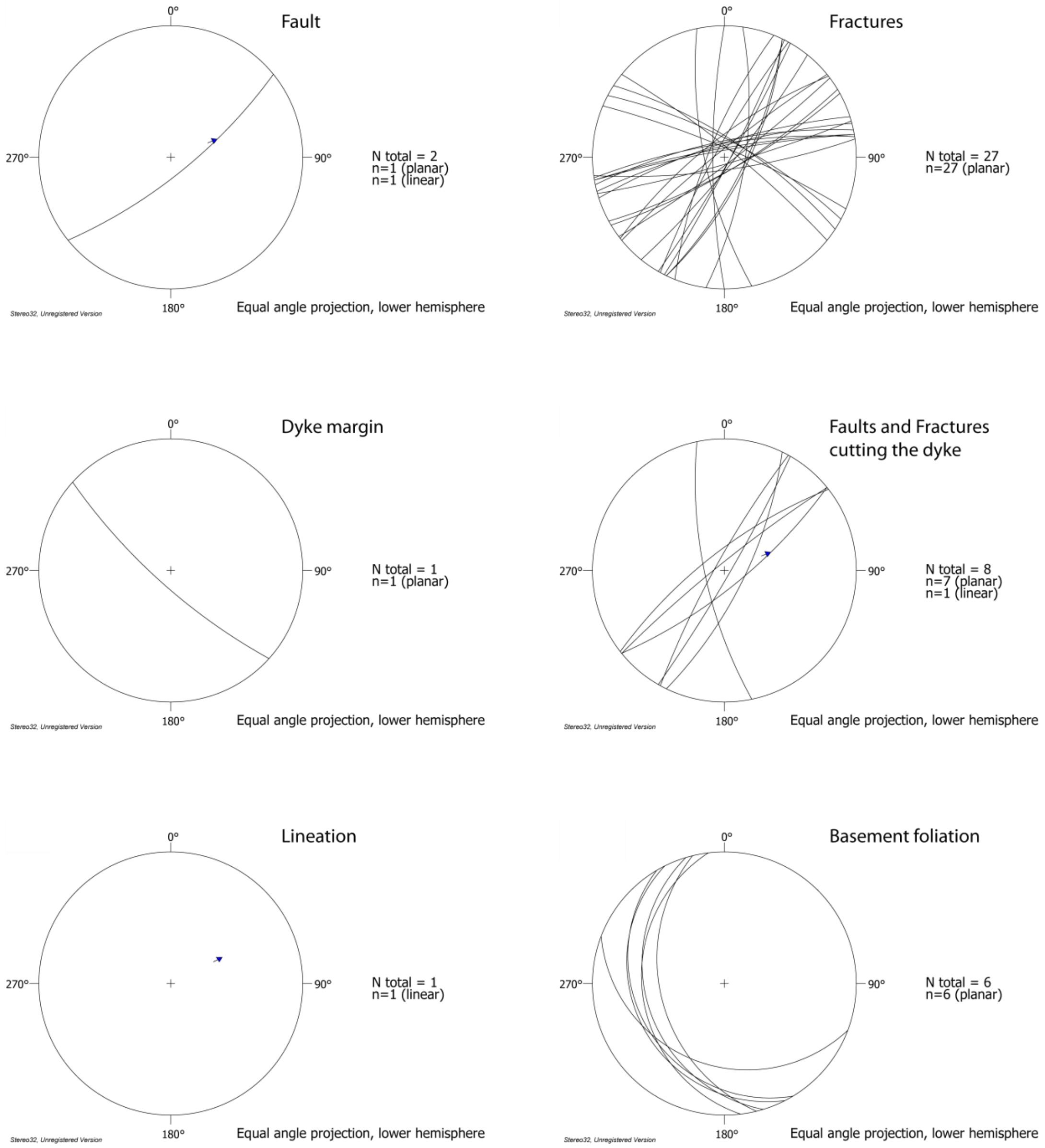


Figure 5.56. Stereonets of field data collected on Ilha de São Francisco. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.5.4 The Ponta Grossa Region - Discussion and Summary

Similar to the Serra do Mar region, the dominant trend of faults, fractures and dykes in this area is significantly oblique to the regional extension direction. Structures can be observed in this region that are typical of strike slip or obliquely deforming areas. These structures include Riedel shears and shallowly plunging slickenlines, and are seen at Ilha do Mel and Ilha do São Francisco. Fractures and faults with apparently mutually cross-cutting relationships and polymodal geometries are indicators of non-plane strain (Krantz, 1988; Reches, 1983), and therefore could also hint at a transtensional origin for the structures in the area. Reverse faults observed at Guaratuba are not inconsistent with a transtensional origin, as a compressional element is often observed as part of transtensional deformation (De Paola et al 2005; Chapter 3.2), though their NW-SE geometry suggests this compression may be unrelated to the rifting event.

The table below (table 5.3) shows the main trends of structures observed at the outcrops in the Ponta Grossa Domain, interpreted according to the McCoss construction (McCoss, 1986). It shows that the deformation at all of the outcrops can be considered transtensional, and that the main trends of fractures at Guaratuba and Ilha de Sao Francisco can be considered to have formed in a wrench-dominated setting. The trends of faults across the region are extension-dominated, though the presence of shallowly-plunging lineations suggests that they have deformed obliquely. Structures at Ilha do Mel are all extension-dominated (according to the McCoss construction), although there are a large number of structures, including NW-SE trending dextral faults which do not fall into the dominant trend, and therefore were not considered

Outcrop name	Structures measured	main trend of structures	extension direction	Angle A	TT?	Field of transtension - McCoss (1986)
Ilha do Mel	Faults	021	090	159	Yes	General Extension
	Fractures	146	090	146	Yes	General Extension
Ilha de São Francisco	Faults	051	090	129	Yes	General Extension
	Fractures	077	090	103	Yes	General Wrench
Guaratuba	Faults	163	090	163	Yes	General Extension
	Fractures	076	090	104	Yes	General Wrench

Table 5.3. The main trends of structures from outcrops in the Ponta Grossa domain, assessed for transtensional deformation using the McCoss method (McCoss, 1986), and an assumed E-W extension direction, based on oceanic fracture zones. All outcrops are transtensional, and fractures from Ilha de Sao Francisco and Guaratuba fall into the wrench dominated domain.

Similarly to the Serra do Mar region, structures in the Ponta Grossa region closely follow lineament trends, typically with one set of structures, including the dykes and some fractures trending NW-SE, and another set trending NE-SW, although there is clearly a larger deal of complexity than this, especially at Ilha do Mel. The basement across the area all forms part of the Ribeira belt, and structures typically trend NE-SW with small scale variations in structure and foliation. The basement has some influence on NE-SW trending structures, and direct evidence for reactivation can be observed at Ilha do Mel, but it does not influence the NW-SE trending dykes. In the absence of other evidence, it seems most reasonable to suggest that the Ponta Grossa arch - a structural high throughout the Mesozoic - is the main influence on the structures (Strugale et al., 2007).

The dykes observed in the Ponta Grossa region trend NW-SE, parallel to the other dykes in the Ponta Grossa swarm (Coutinho, 2008), and a major lineament set in the area (Chapter 4). Some faults and fractures trend parallel to these dykes, and show dextral offsets, which is consistent with an E-W extension direction for the region. Less evidence is observed here for dykes intruding along pre-existing structures, with the exception of the small dyke branches at Guaratuba. The close geometric parallelism between the dykes and many of the fractures, however, suggests that they may have formed at a similar time. These dykes are most likely to be syn-rift based on their doleritic composition and the dating of NW-SE dykes in the Ponta Grossa arch by a number of authors (Renne et al., 1996; Turner et al., 1994)

Regionally, the kinematics and geometries observed at these outcrops support the 'triple junction model', with a NE-SW sinistral arm – Serra do Mar, and a NW-SE dextral arm. If this model is the case, we would expect faults and fractures in the Florianopolis dyke swarm, which would be the third arm of the triple junction, to show normal kinematics (see next section). A key difference between the Ponta Grossa region and the Serra do Mar is that while we see structures cutting the dykes, trending NNE-SSW, we also see a variety of other orientations. Where we observe kinematic evidence, these structures are sinistral, and many have strike-slip lineations, suggesting that in this region, the post-dyke faults deformed differently to those NNE-SSW trending, normal-offset post dyke faults in the Serra do Mar region. This may be a manifestation of large-scale partitioning of deformation following dyking, or may be due to the reactivation of these faults and fractures by later structures with different kinematics. Reactivation of brittle structures across the margin is likely, due to significant post-rift deformation during the uplift of the coast-parallel mountains, and during neotectonic deformation. All of these events are likely to be kinematically different, as shown by Ferrari (2001). Dating these faults and fractures is impossible, other than that they have formed after the intrusion of the dykes.

5.6 The Florianopolis Dyke Swarm

Santa Catarina Island (often known as Florianopolis) is the main location in which the Florianopolis dyke swarm was studied, with several outcrops of dykes and faults in the area (Fig. 5.58A,B). Four main outcrops were studied on the island(Figure 5.57,5.58).. Dykes in the Florianopolis region have been dated, and are syn-rift (135Ma) in age (Raposo et al., 1998).

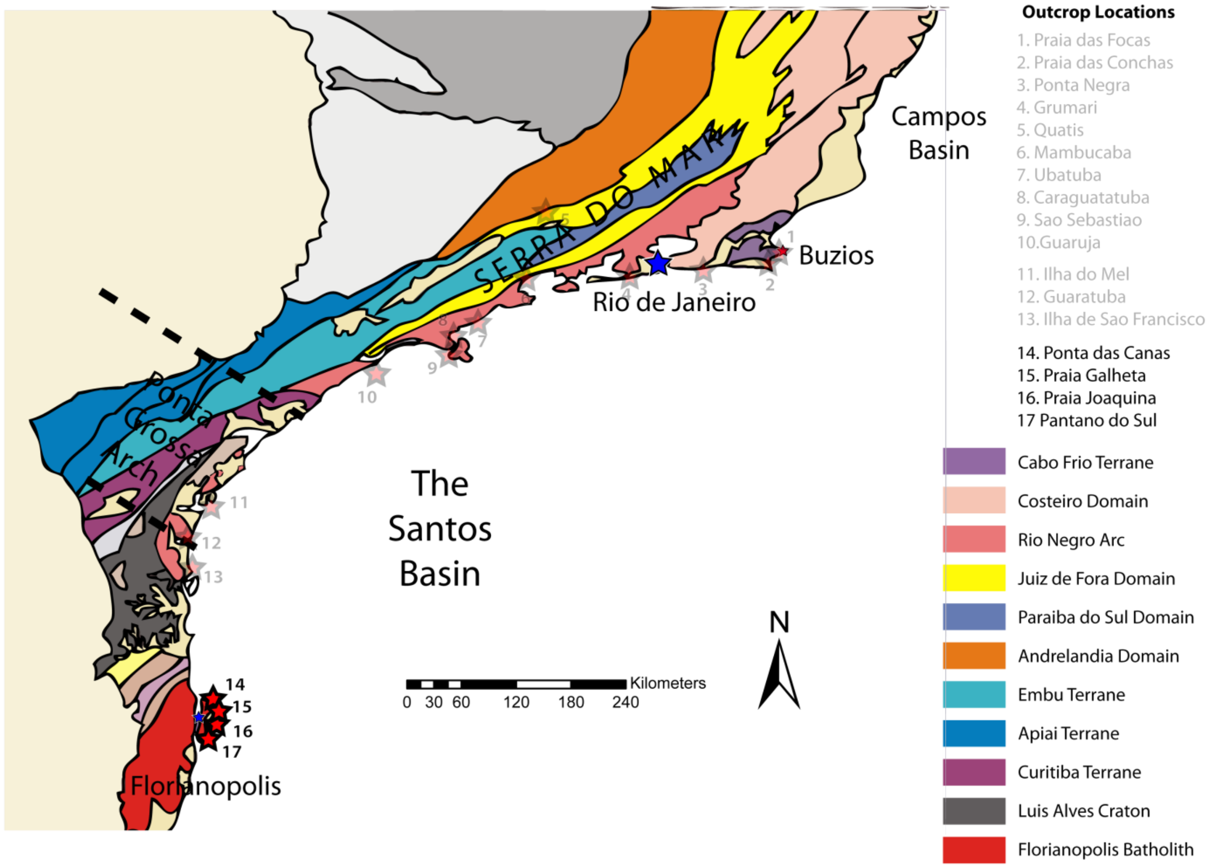


Figure 5.57 – Terrane map of the study area, after Passarelli et al. (2011), showing the locations of studied outcrops. Numbers 14-17 (highlighted) are the outcrops in the Florianopolis domain, and are all situated in the region of the Florianopolis Batholith in the south of the onshore study area.

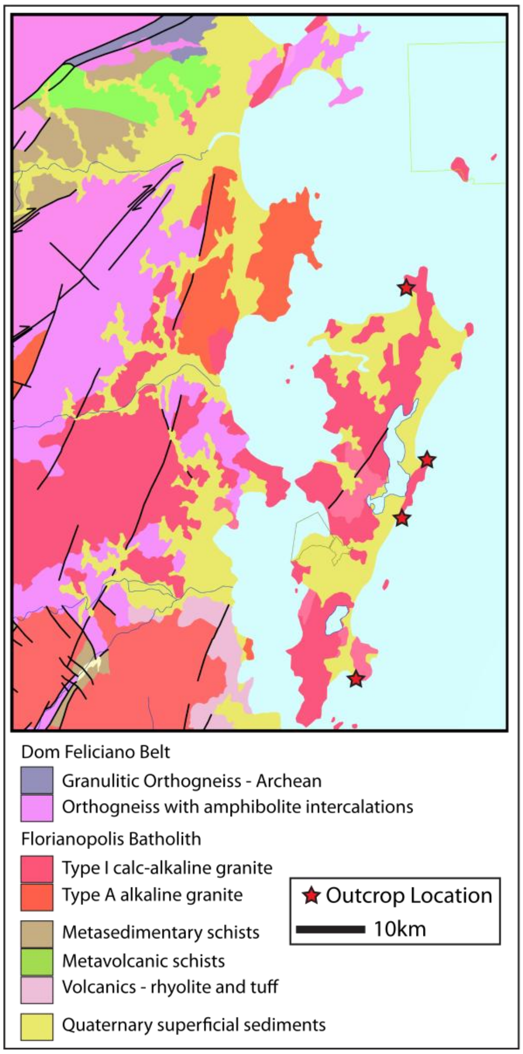


Figure 5.58 A.A Google earth aerial image of the island of Florianopolis, where 4 of the outcrops from the Florianopolis dyke swarm are located. B. Geological map of the study area, showing key lithologies and structures (black lines).

5.6.1.1 Praia Galhetas, Florianopolis, SC

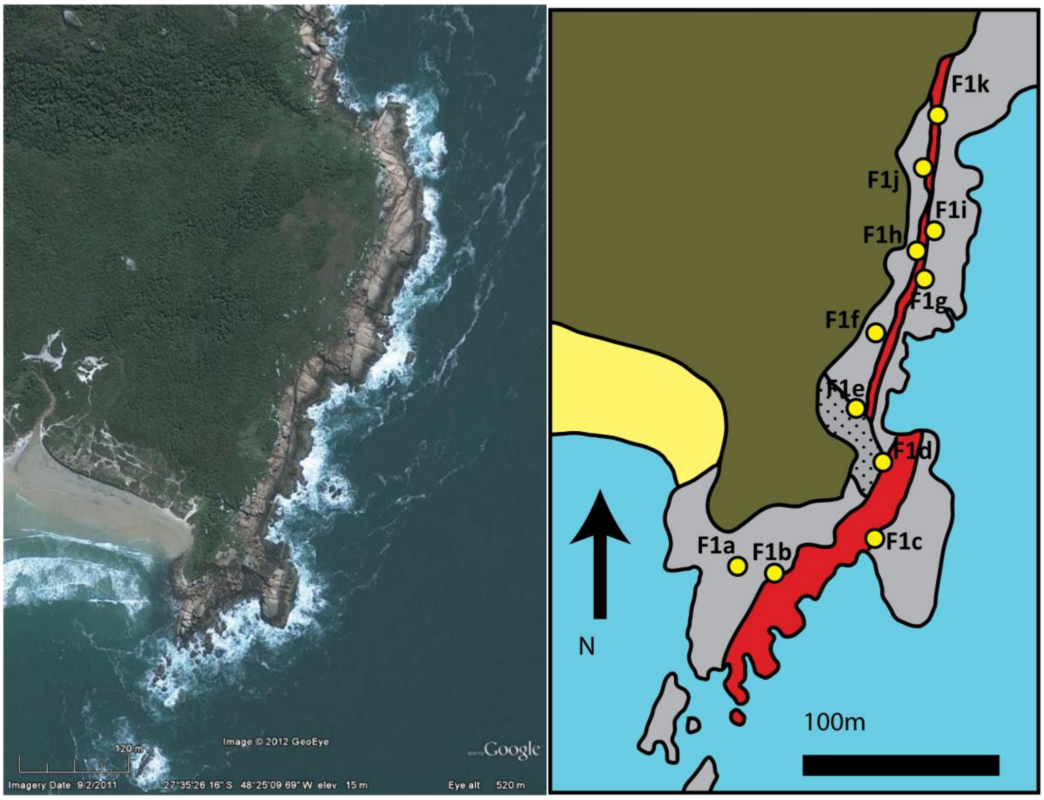


Figure 5.59 A.A Google earth aerial image of the outcrop at Praia Galhetas. B. simplified geological map of the outcrop, showing basement (grey), and dykes (red). Sea (blue), beach (yellow), rubble (dotted), and areas where outcrop is obscured by vegetation (green) are also coloured.

Outcrop description

Several hundred square metres of outcrop can be seen to the north of Praia Galhetas, on an elongate strip, much of which is exposed to large Atlantic storm waves (Fig. 5.59A). Two well-exposed, NNE-SSW-trending dykes can be observed at this outcrop (Fig. 5.59B), intruding unfoliated granitic basement of the Neoproterozoic Florianopolis batholith (chapter 2.3.1.4) Multiple set of fractures and some faults are also present here.

Outcrop-scale structures

The basement is isotropic granite, with little evidence of foliation (Fig. 5.61A).

Two dykes can be observed, and are doleritic in composition. The dyke margins trend NNE-SSW, although some variation in orientation is due to the presence of xenoliths and jogs in the dyke margins (e.g. Figure 5.60). Some of these xenoliths show internal fracturing which does not propagate into the dyke, suggesting the fractures formed before the intrusion of the dyke.

Faults display a wide array of orientations, but the only consistent set trends NNE-SSW. One large fault zone is present (Fig. 5.62B), with some fractures containing breccias (clast size >4-10cm, with no evidence for internal structure) and quartz vein material (where seen, veins are up to 15cm wide). Smaller fault zones show red coloured staining both on and around fracture surfaces, and consist of zones with high fracture density, showing slickenline lineations and red discolouration, rather than structures displaying offsets (Fig. 5.61B).

Fractures were observed in a wide variety of orientations, both steeply and shallowly dipping. The dominant fracture sets, however, trend NNE-SSW, parallel to the faults, and NNW-SSE (Fig. 5.63). The faults and fractures cutting the dykes are almost all from the NNW-SSE set and do not trend parallel to the joints in the dykes, which are oriented closer to ENE-SSW (Fig. 5.63). The lineations on faults plunge shallowly, suggesting strike-slip deformation here. Faults and fractures are strongly parallel to the dyke margins, in terms of dip and strike. Changes in the orientation of the dyke margins often coincide with fractures parallel to the 'new' orientation of the margins. The dyke does not appear to follow fractures in orientations other than NNE-SSW and NNW-SSE. NNW-SSE fractures conjugate to a NNE-SSW (dyke-parallel) fracture are observed to be truncated by the dyke. A number of these conjugates appear to have been reactivated, and can be seen cutting the dyke (Fig. 5.62A).

Interpretation

This outcrop shows both the scale of some of the dykes in the Florianopolis swarm, and their clear link with brittle structures. The geometry of the dyke is clearly influenced by brittle structures, and the presence of fractures in xenoliths within the dyke confirms their presence prior to intrusion. The dykes do not infill structures at high angles to the NNE-SSW trend of the majority of structures observed here, and many NNW-SSE-trending structures cut the dykes. This could suggest that there are two fracture events observed at this outcrop.

The doleritic composition of the dykes is consistent with a syn-rift origin, and although their specific ages are unknown, 125-130Ma ages for other dykes on the island, also doleritic in composition, have been published (Raposo et al., 1998). In the absence of any local basement fabrics influencing the orientations of faults, fractures and dykes at this outcrop, it appears that the dominant control on the geometry of this dyke are the fracture sets which existed before its intrusion. The close parallels between the orientations of the dyke margins and the major fracture sets at this outcrop support this conclusion.

Evidence that the dyke has intruded into the fault zone observed to the south of the outcrop suggests that the fault is older than the dyke (Fig. 5.62C).

The geometries of some fractures are consistent with dextral strike-slip deformation (Fig. 5.61c), but since these geometries are only seen at one outcrop, this is far from regionally conclusive, and inconsistent with regional E-W extension. In addition, the shallowly dipping lineations on faults are inconsistent with what should be expected under E-W extension. The NNW-SSE trending fractures that cross-cut the dyke indicate that there has been a later stage of deformation in this area (Fig. 5.60). One set of dyke-parallel fractures, with conjugate structures, appear to have been active at some time after the dyke was intruded (Fig. 5.62A). The dyke-parallel nature of these fractures, and the fact that not all of the conjugates cut the dyke suggest that these fractures existed before the dyke intruded, and have been reactivated since.

Large xenoliths within the dyke can often be observed in close proximity with changes in the orientation of the dyke margin. This suggests that the xenoliths have not travelled far within the dyke (Fig. 5.60).

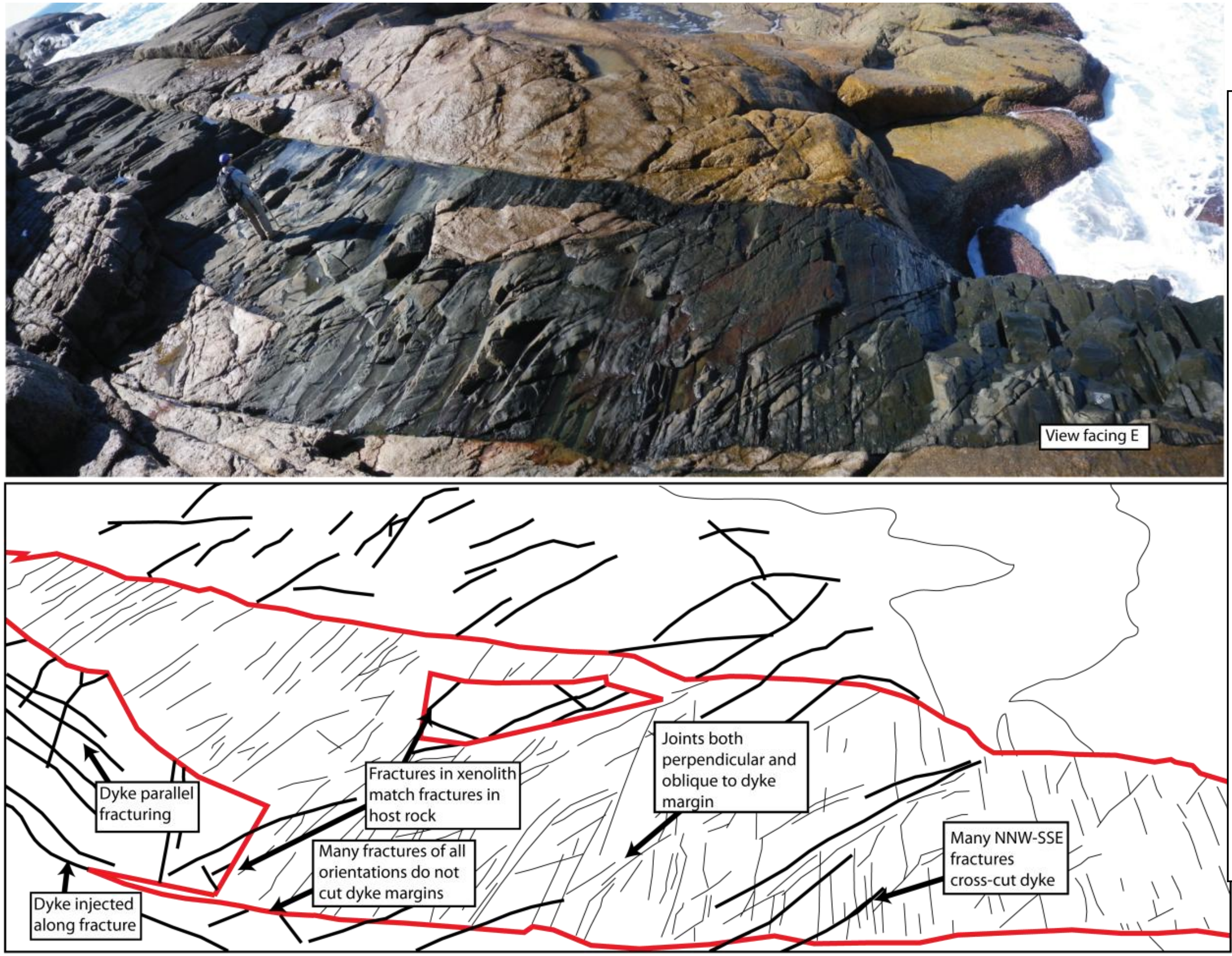


Figure 5.60. A panoramic image of the northernmost dyke at Praia Galhetas, with interpretation below. The dyke appears to have been heavily influenced by pre-existing brittle structure, with its margins, and those of the large xenolith (when restored) closely parallel fracture sets in the basement. Fractures within the xenolith can be correlated with fractures in the granite, when it is restored to its original position. Where this 'corner' is, on the dyke margin, the dyke continues to propagate along a fracture in the basement. Two sets of structures can be seen within the dyke. The first are margin-perpendicular joints, and probably formed when the dyke cooled. The second set is oblique to the margins, and many cut both the dyke and basement. These fractures clearly formed after the intrusion of the dyke.

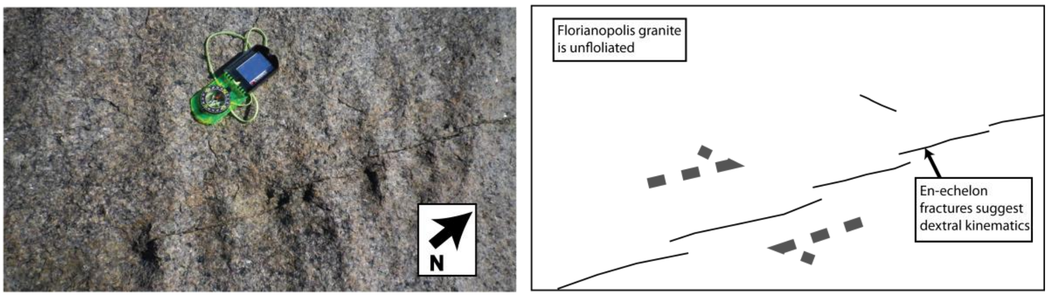


Figure 5.61A. NNE-SSW trending en-echelon fractures within the granite at Praia Galhetas. These individual fractures do not accommodate any apparent offset, but their geometry suggests dextral kinematics.

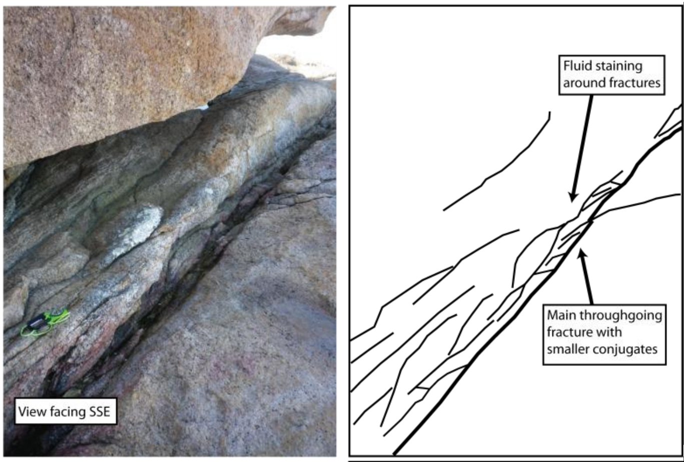


Figure 5.61B. This fault consists of a series of lenses of granite within a larger structure. The fractures within the fault are stained red, and trend at a high angle to the dyke margin. No evidence can be seen of this particular fault cutting the dyke.

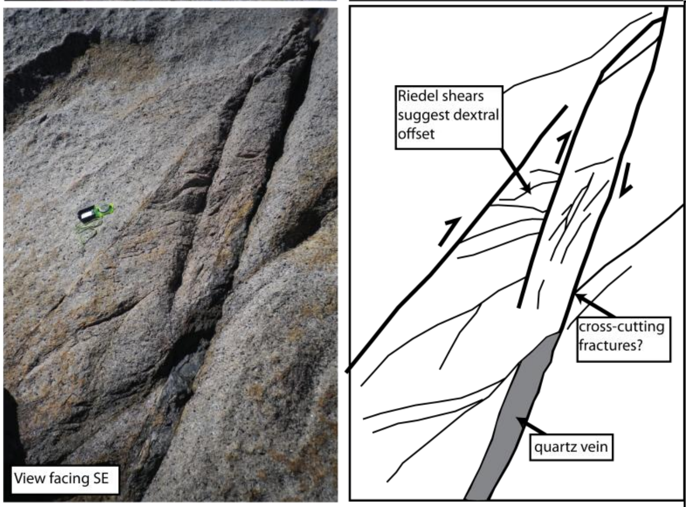


Figure 5.61C. Apparent dextral kinematics of fractures in the granite at F1a, away from the dyke. A quartz vein trends parallel to one of these structures, suggesting they may have been formed during a hydrothermal event. The sense of deformation on these structures has been derived from their geometry, and that of the smaller conjugate fractures between them.

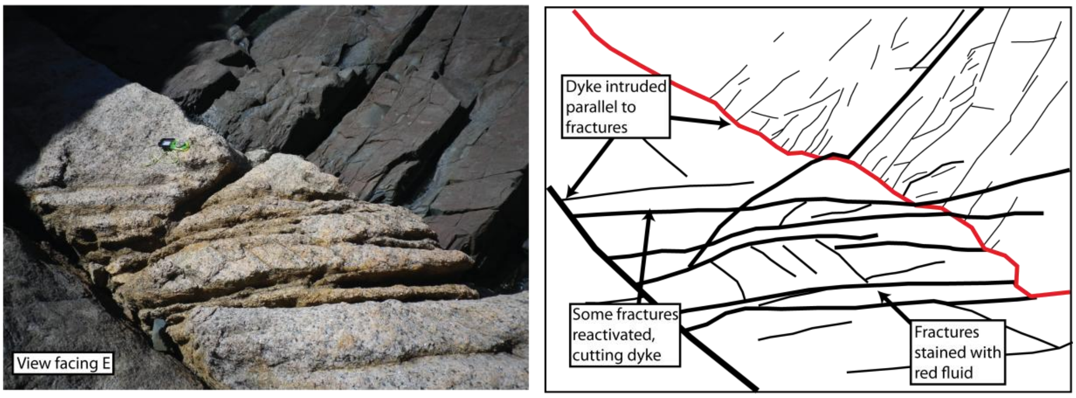
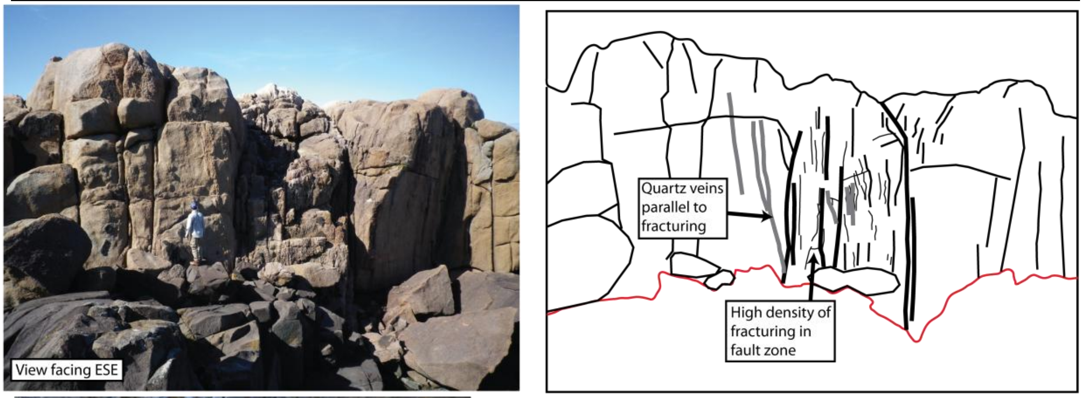


Figure 5.62A. The dyke at Praia Galhetas appears to have intruded along pre-existing fractures. Here, NNW-SSE trending fractures appear to link the dyke margin and a larger NNE-SSW trending dyke parallel fracture. Some of these structures have been reactivated, cutting the dyke, but many are truncated by the dyke margin. I interpret these structures as conjugate fractures, which formed prior to the dyke. The dyke intruded along one of these structures, then later, the smaller NNW-SSE trending fractures were reactivated.



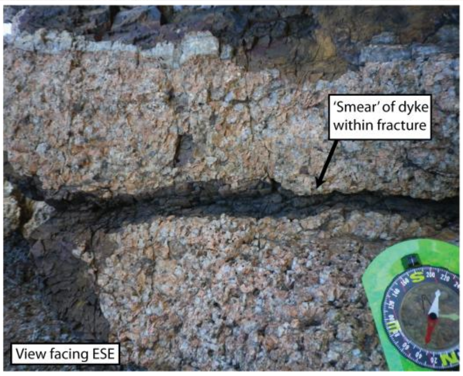


Figure 5.62B (above). A wide fault zone composed of a large number of sub-parallel fractures is truncated by the wider of the two dykes at Praia Galhetas. Many fractures show oblique-slip lineations, though due to the relatively homogeneous granite, amounts and senses of offset are difficult to ascertain. Within many of the fractures, quartz veins, and breccia with quartz based matrix can be seen.

Figure 5.62C (above). Within the fault zone, smears of dyke material can be seen within the fractures, highlighting the fact that these fractures were present before the intrusion of the dyke, and that dyke material was clearly able to infill them.

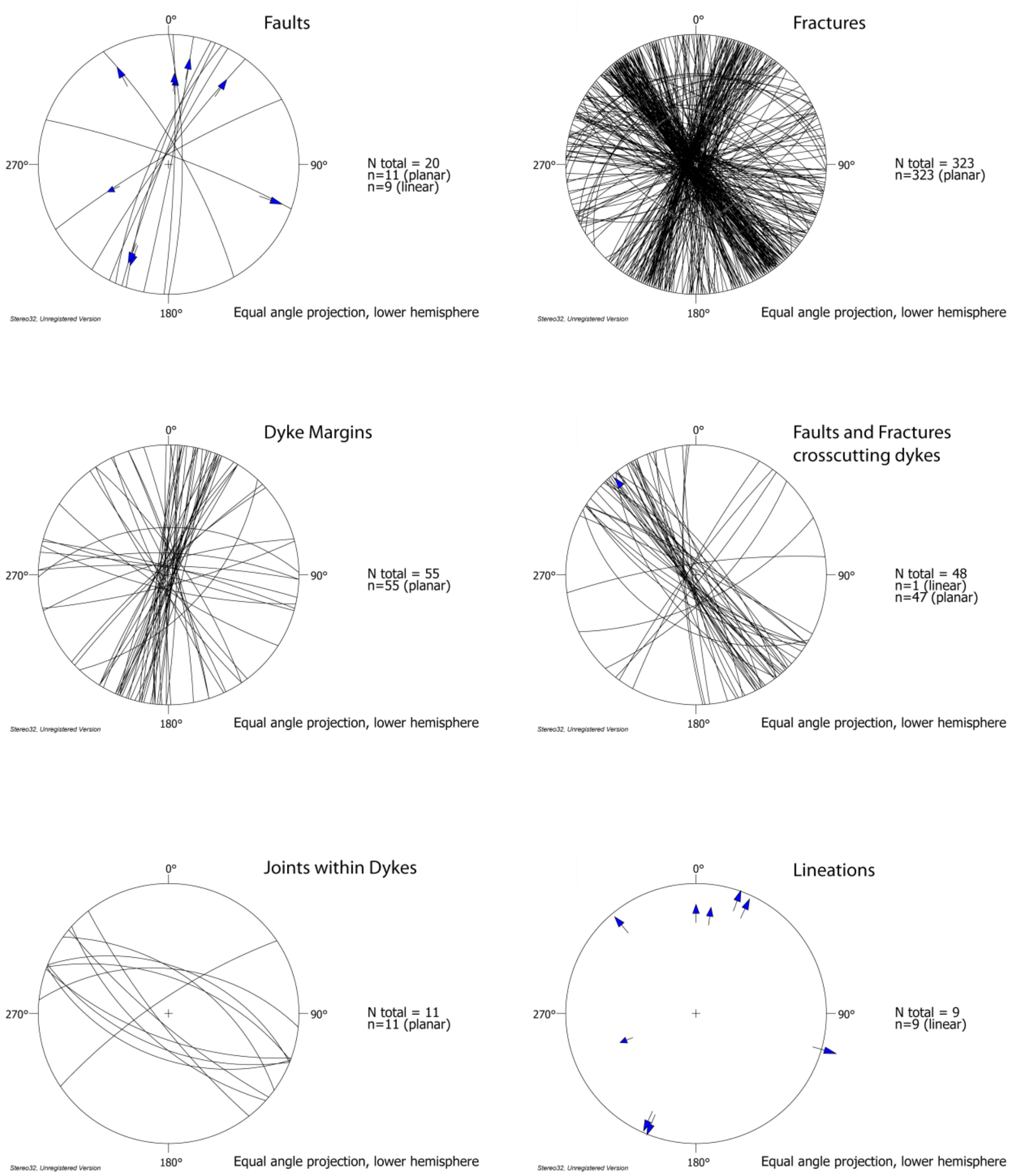


Figure 5.63. Stereonets of structural data collected at Praia Galhetas. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.6.1.2 Praia Joaquina, Florianopolis, SC

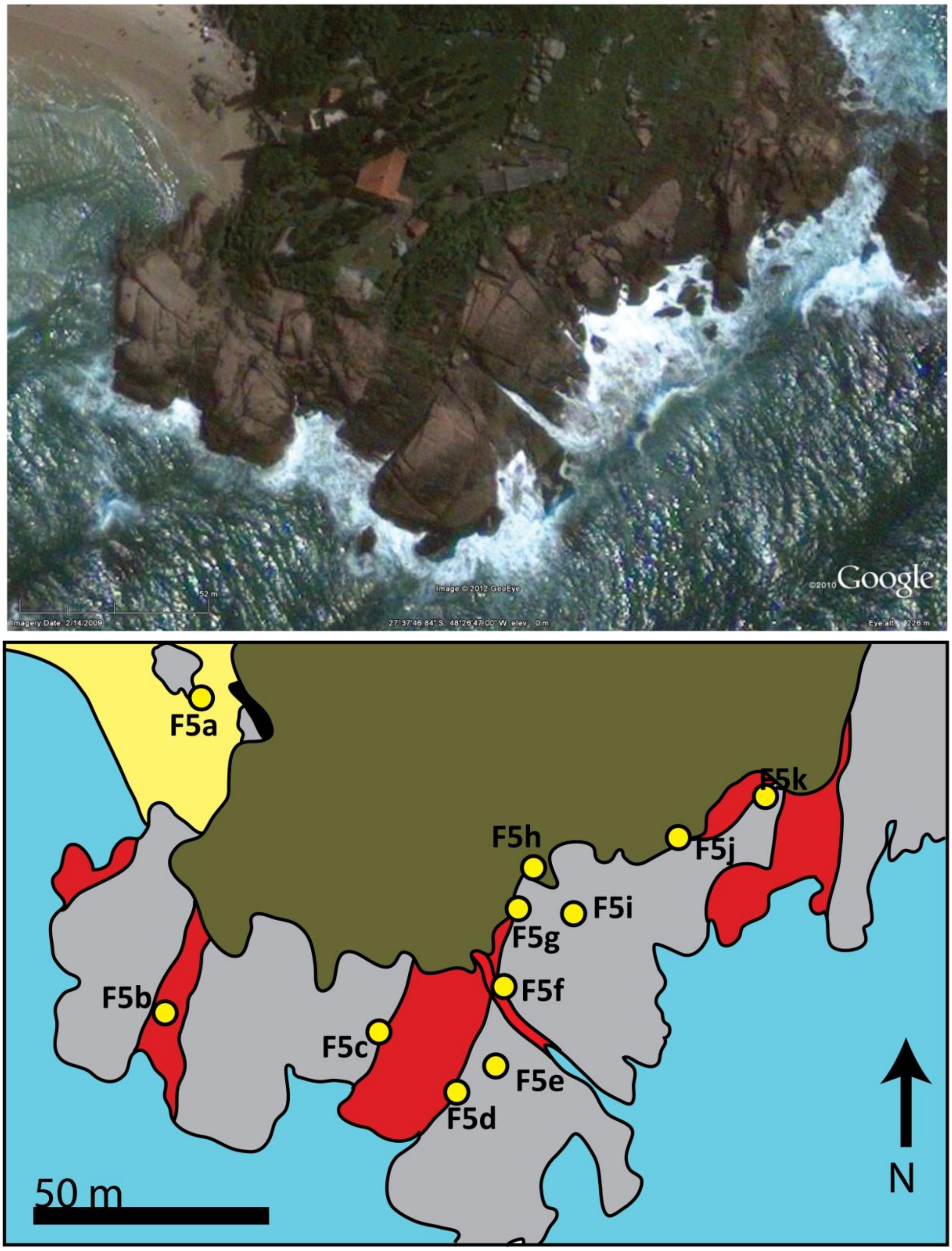


Figure 5.64 A. A Google earth aerial image of the outcrop at Praia Joaquina. B. simplified geological map of the outcrop, showing localities visited (yellow circles), basement (grey), and dykes (red). Sea is Blue, Beach is Yellow, and areas where exposure is masked by vegetation are green.

Outcrop description

The outcrop at Praia Joaquina is located at the northern end of a large beach. Steeply sloping basement, and incised gullies (containing NNE-SSW and NNW-

SSE trending syn-rift dykes) comprise the exposure, which is approx 150m in length, around a small headland (Fig. 5.64A) . The basement consists of Neoproterozoic Florianopolis batholith granitic basement (chapter 2.3.1.4) (Fig. 5.64B). The basement is also cut by a large number of faults and fractures.

Outcrop-scale structures

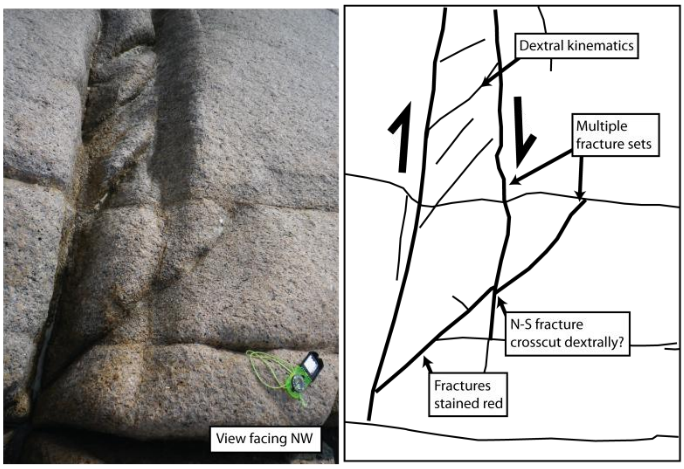
Basement rocks at this outcrop comprise unfoliated granite. No evidence for pre-existing structures was found within the granite, other than a series of quartz veins which are described later. This outcrop shows dykes trending NNE-SSW and NNW-SSE. Both large and small younger dykes (i.e. those which crosscut other dykes) can be observed (Figs 5.67A and B), and the composition of each set of dykes appears similar. Cross-cutting relationships between these dykes appear complex. A NNE-SSW set, similar to the dykes at Praia Galhetas is cross-cut by a NNW-SSE set (Figs 5.67A, B), with the exception of a NNW-SSE trending foliated dyke (Figs 5.66A-D). A foliated dyke was observed at waypoint F5i (Fig. 5.64), and contains elongate lenses of basement rock parallel to the dyke margins. The apparent foliation trends parallel to the dyke margins, and is not typical of other dykes observed across the margin. Along strike, a boundary between the foliated and an unfoliated dyke can be observed. The uncleaved dyke follows the same orientation and is the same width as the foliated dyke. The foliated dyke is crosscut by a NNE-SSW trending dyke.

Similarly to Praia Galhetas, two main fault and fracture orientations can be observed, although there is a significant amount of scatter in the data, particularly in the fracture dataset (Fig. 5.68). Faults and fractures both trend NW-SE and NNE-SSW which mirrors the dyke margins (Fig. 5.68). Riedel-shear type geometries of some NW-SE fractures suggest dextral kinematics (Fig. 5.65A). Only one fracture can be observed cutting the dykes, trending NW-SE, sub-parallel to the main joint set, which is perpendicular to the margins of the NNE-SSW dyke set. Slickenline lineations measured are shallowly plunging, consistent with strike-slip deformation (Fig. 5.68).

Interpretation

The multiple sets of dykes observed at this outcrop appear to have mutually cross-cutting relationships, suggesting that they all formed contemporaneously. The foliated dyke is, however the only example of a NNW-SSE dyke being cross-cut by a NNE-SSW dyke that has been observed during the present study. The cause of the foliation is unclear. Whether the strongly cleaved dyke is an older metamorphosed dyke, or has been sheared during the intrusion of the younger dyke is unclear, but the absence of foliation or cleavage in the country rock suggests that the event or process forming the cleavage is strongly localized to within the dyke. If the sheared dyke is significantly older than the other dykes at the outcrop, it makes it more likely that the other NNW-SSE dykes represent a younger event than the NNE-SSW dykes, and would show that either the orientation of stress or the dykes changed between the intrusions of the two sets.

The margins of the majority of dykes appear to have been locally controlled by fracturing (Figs 5.65B, C), although this local relationship is not the case across the entire outcrop, with some dyke margins appearing to show a primary intrusive contact with basement. Nonetheless, the close parallelism between the dykes and fractures in the basement suggests that there is probably a relationship between the two, and that the same processes are responsible for determining the orientations of both the fractures and dykes.



5.65A. Apparent dextral kinematics on two fractures, linked by Riedel shears. The fractures at Praia Joaquina are relatively discrete, and do not seem to change in density near to dykes. Two sets are seen here at 90° to each other, which is not common across the outcrop, or the area as a whole.

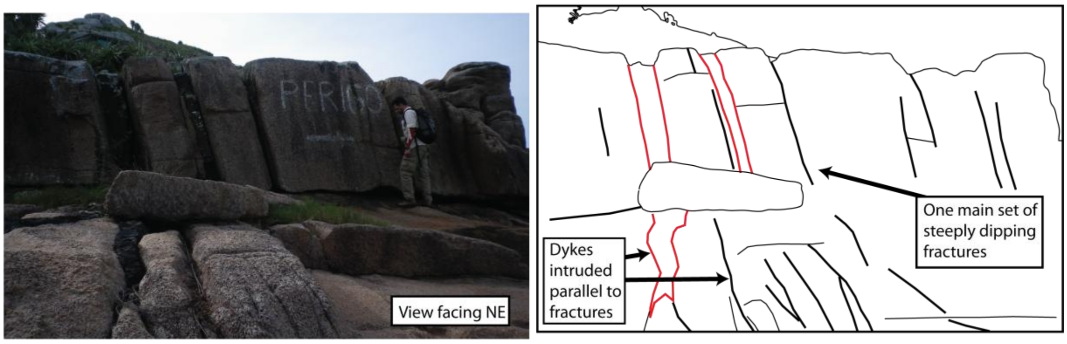


Figure 5.65B. Two small dykes, seen in the small cliff at locality F5g at Praia Joaquina, with steeply dipping, clearly dyke parallel fractures. These dykes are doleritic in composition, with large feldspar phenocrysts. These dykes are crosscut by a NNW-SSE trending dyke, just behind the position where the photo was taken. This crosscutting can be seen in Figure 5.83A.

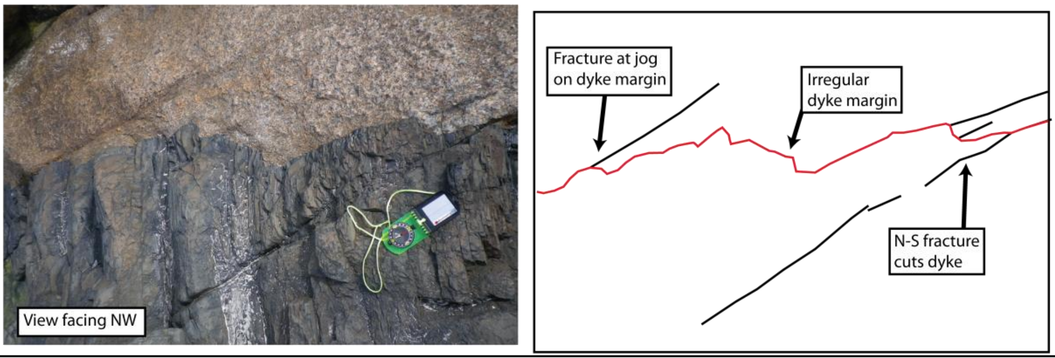


Figure 5.65C. a close-up ofa dyke margin at Praia Joaquina. Fractures occur at jogs in the dyke margin. It is unclear whether the fractures have formed as a result of the jogs, or the other way round. One of the fractures appears to propagate into the dyke, but the others do not.

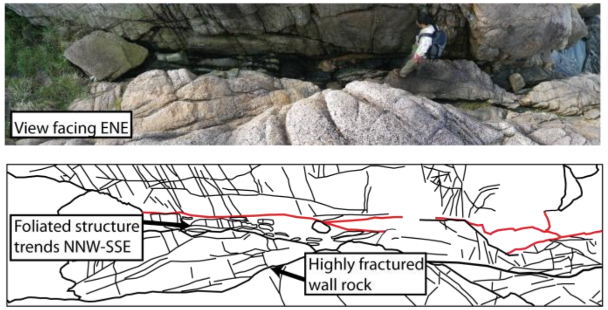


Figure 5.66A (top, middle). The sheared dyke locality at Praia Joaquina, showing the large amounts of fracturing in the granite.

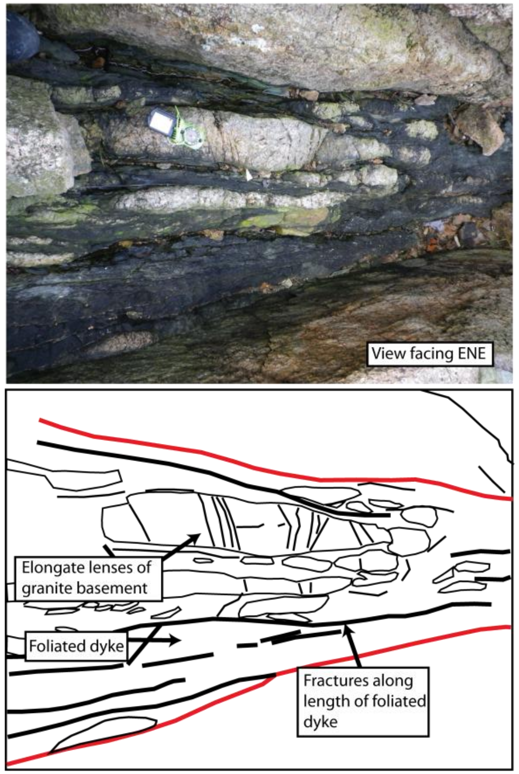


Figure 5.66B (top, Left). A close-up of the elongate xenoliths of granite and the foliated dyke. The foliation appears to have been reactivated by later fractures.

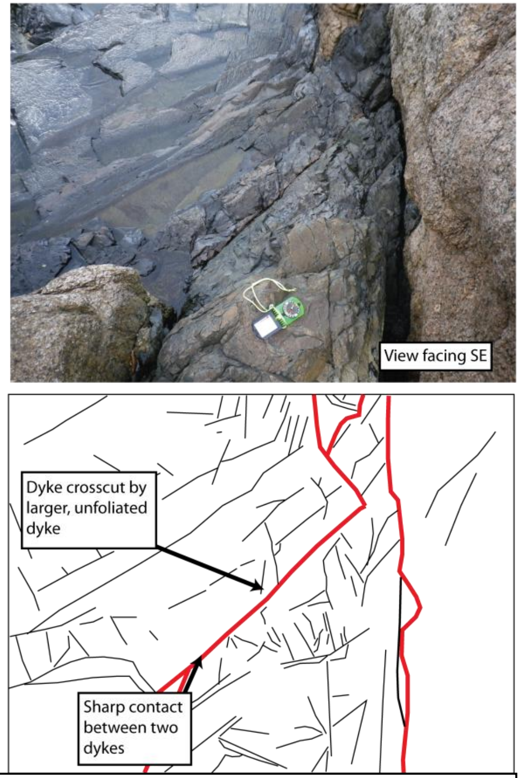


Figure 5.66C (top, right) The dyke is cut by a larger, NNE-SSW trending dyke. Could the foliated dyke represent a much older magmatic event than the other syn-rift dykes? seen

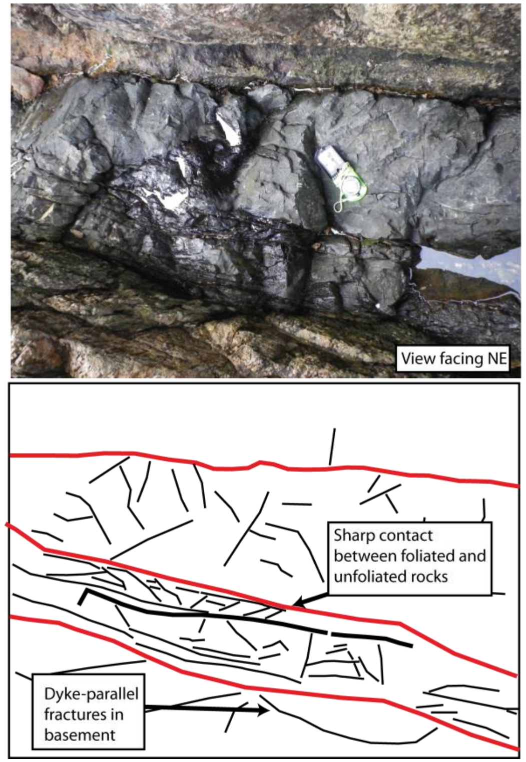


Figure 5.66D (bottom, middle). The contact between the foliated and unfoliated dykes. It is unclear whether this contact is intrusive, or if the foliation is highly localized. within a dyke

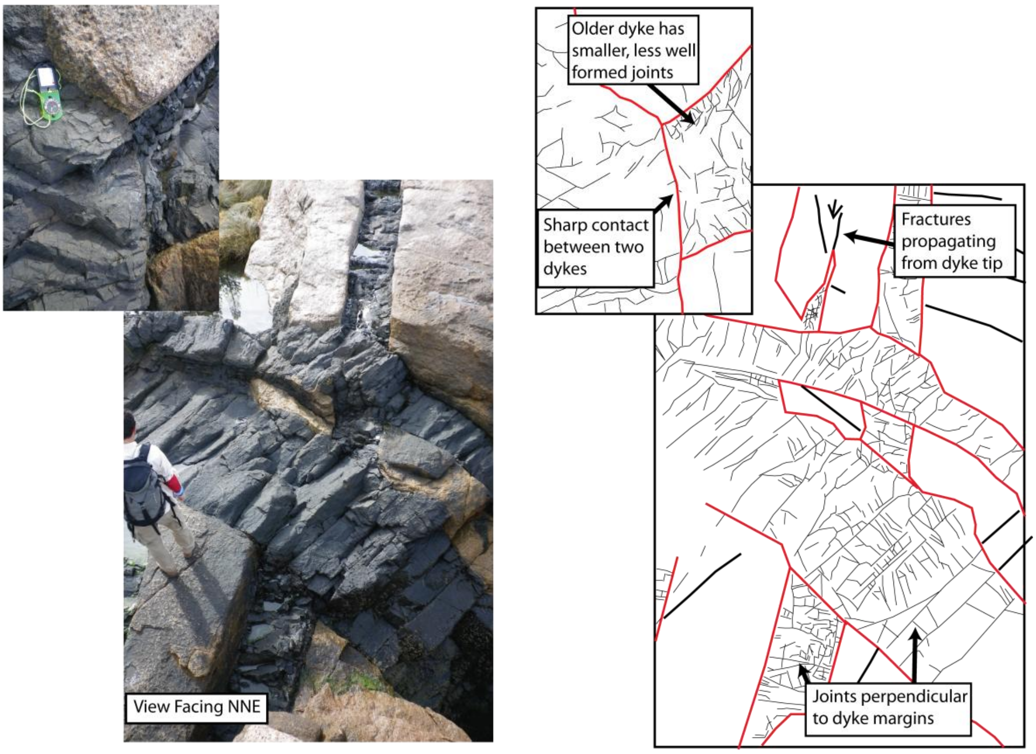


Figure 5.67A. The smaller, NNW-SSE dyke cuts the larger NNE-SSW dyke at Praia Joaquina. This is the first example seen from across the area of crosscutting dykes, though more are seen at this outcrop. Both dykes are doleritic in composition. Whilst many fractures are seen in the granite basement at this outcrop, few are seen to cut dykes. The joints within the dykes are consistently perpendicular to their margins, consistent with having formed as the dykes cooled. The sharp contact between the dykes (inset), does not appear to be related to fracturing, though each dyke does trend parallel to a fracture set in the granite.

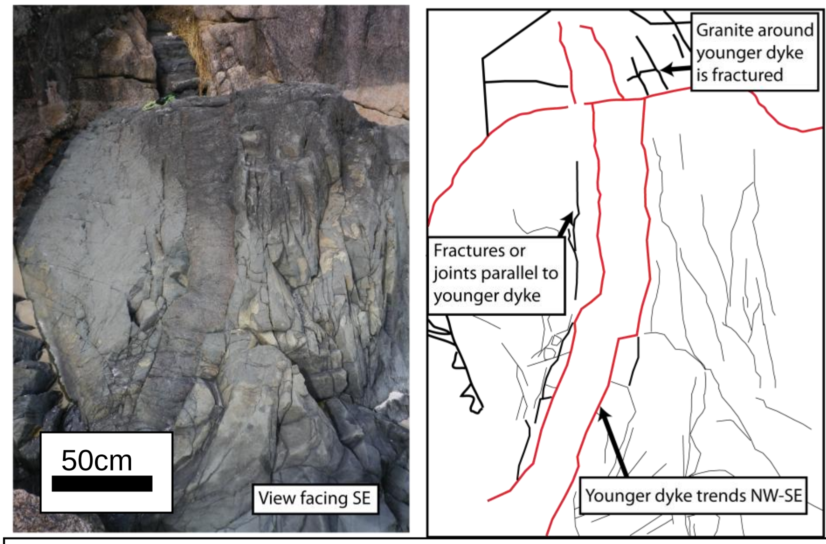


Figure 5.67B. Another dyke, seen crosscutting a larger NNE-SSW trending dyke at the western end of the outcrop at Praia Joaquina. The amount of fracturing within the larger dyke increases towards the smaller structure, possibly due to fracturing as it intruded. Fractures are also seen in the granite, parallel to the younger dyke, but none can be traced into the larger dyke.

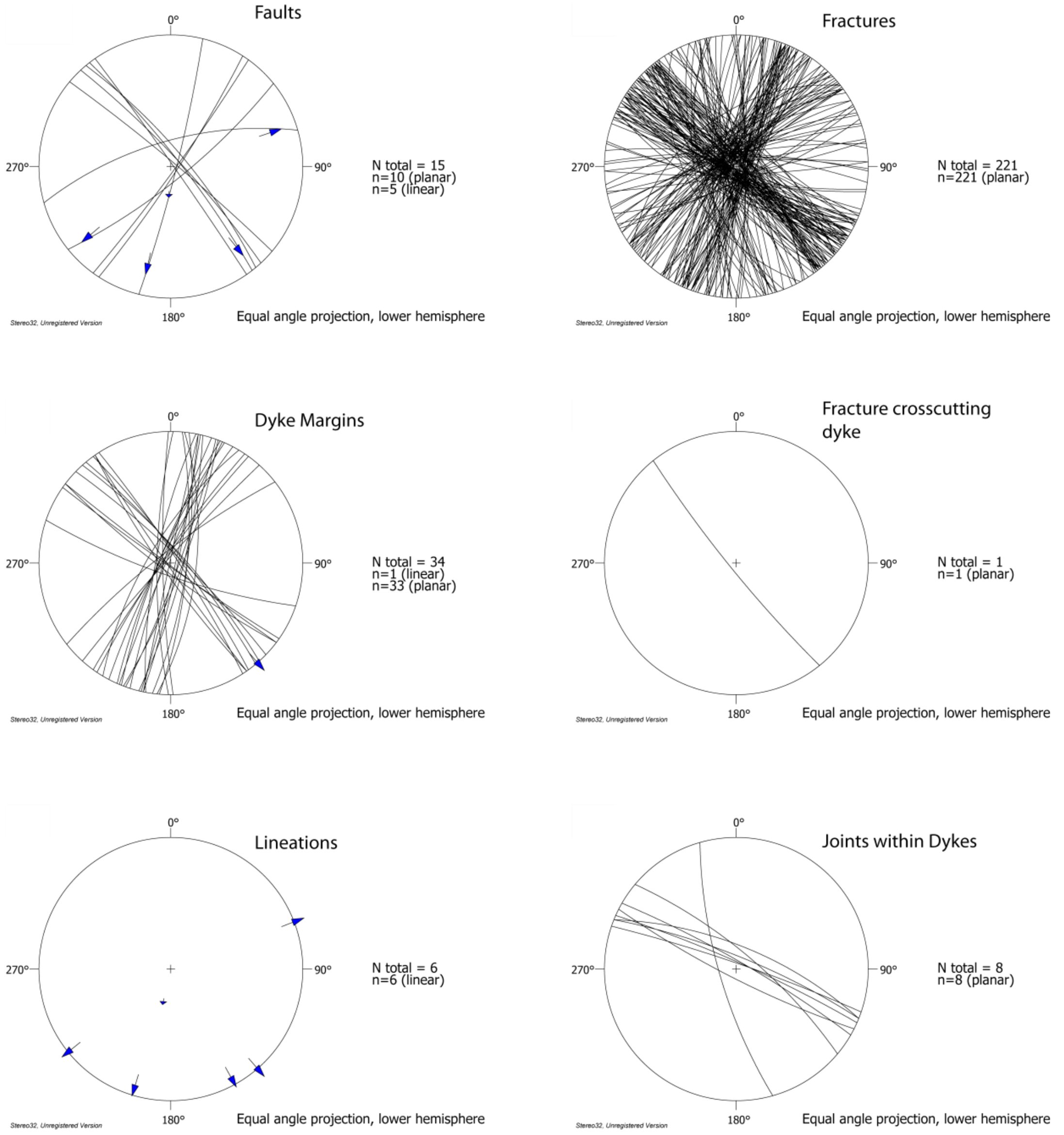


Figure 5.68. Stereonets of field data collected at Praia Joaquina. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.6.1.3 Ponta das Canas, Florianopolis, SC

Figure 5.69. A Google earth aerial image of the outcrop at Ponta das Canas, showing localities visited (yellow circles).

Outcrop description

The majority of the exposure at this outcrop consists of a 30m long, 1m wide strip of exposures which are accessible at low tide. On the beach to the south of the outcrop, isolated exposures can be seen, and a 10m^2 area of scattered boulders and in-situ basement can be seen to the north (Fig. 5.69), A large fault can be observed at the northern edge of the beach at this locality, cutting Neoproterozoic granitic basement of the Florianopolis batholith (chapter 2.3.1.4).

Outcrop-scale structures

The country rock at Ponta das Canas is granite of the Florianopolis batholith, and shows little in the way of pre-existing structure.

While the edges of the NNE-SSW trending fault zone cannot be observed directly, fractures within the fault trend roughly N-S and show broadly normal kinematics (Fig. 5.70A). The fault shows a well-developed fault breccia, with strong fracturing and NNE-SSW trending quartz veins. The breccia is pale red in colour, and consists of well-rounded clasts between 0.5 and 5cm in size (Fig. 5.70B). The matrix is fine grained and red in colour, and does not appear to be foliated. Fractures in the country rock are fewer and further apart than those from the fault zone, and show halos of red fluid staining (Fig. 5.70C).

Faults measured at this outcrop, barring two, all trend NNE-SSW, and dip steeply, although the faults trending closer to N-S dip less steeply (Fig. 5.71). Based on slickenlines, these faults all have normal kinematics. The other faults trending NW-SE have more shallowly dipping lineations, consistent with oblique-slip. The fracture dataset is more scattered, although two main sets are observed, trending NNE-SSW and NNW-SSE (Fig. 5.71). These sets are observed both within the breccia and in the granite basement.

Interpretation

The lack of any dykes or structures of a known age make dating this fault difficult, although its geometry and kinematics are consistent with a syn-rift origin. The red colour of the breccias reflects both the granite that has been faulted, and also Fe-rich fluids which have circulated during faulting. Halos around fractures away from the main fault could also have been caused by these fluids, although these could result from recent meteoric fluid, rather than fluid which circulated during faulting. Quartz veins within the breccia show crack-seal textures, suggesting multiple opening events.

This was the first large fault observed in the Florianopolis swarm, and the high level of weathering has significantly reduced the exposure. The fault has clearly accommodated a large amount of offset, shown by the well-developed breccia, and the vast majority of lineations show that the fault had a dip-slip offset, supporting an E-W regional extension.

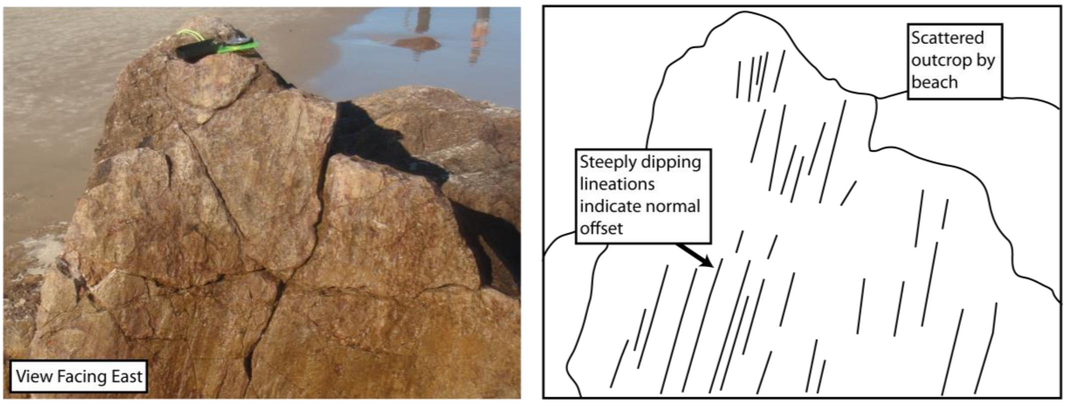


Figure 5.70A. Dip slip slickenlines on a partially exposed fault surface at the end of the beach at Ponta das Canas. These faults trend NNE-SSW, and their dip slip kinematics is consistent with E-W regional extension. These faults are some of the only structures on the island of Florianopolis with consistently dipping slickenline lineations.

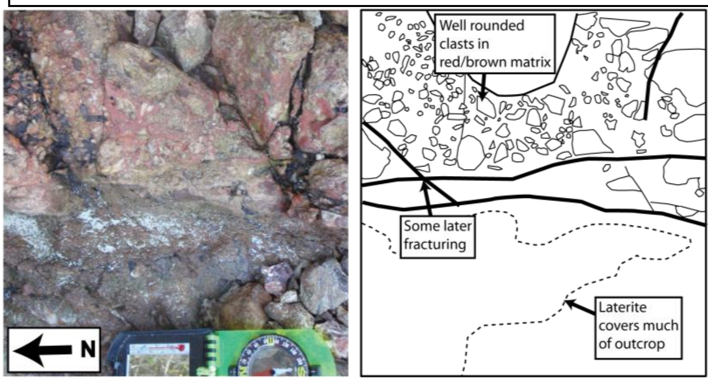


Figure 5.70B. The breccia at Ponta das Canas consists of a large number of small, relatively well rounded clasts of granite in a red/brown matrix. Later fracturing cuts the breccia. Much of the outcrop is highly lateritised.

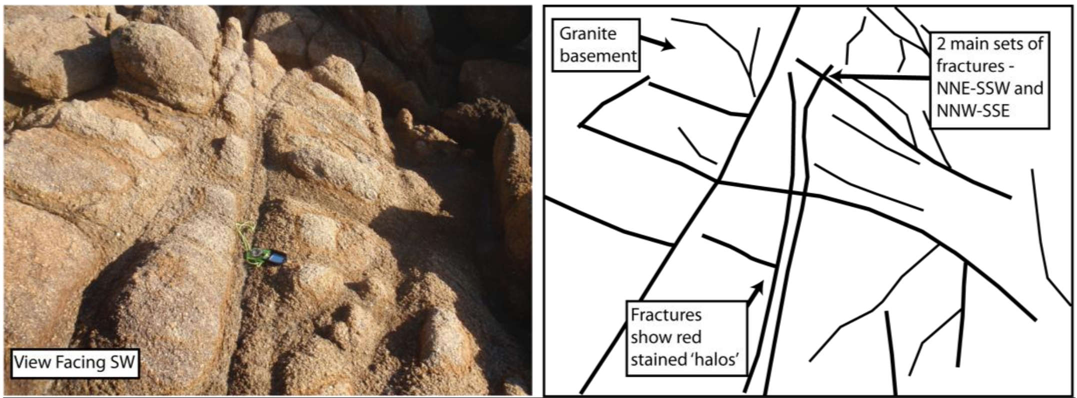
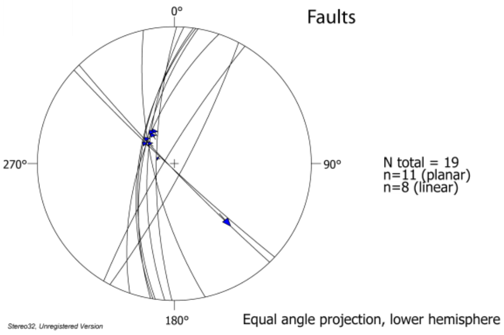
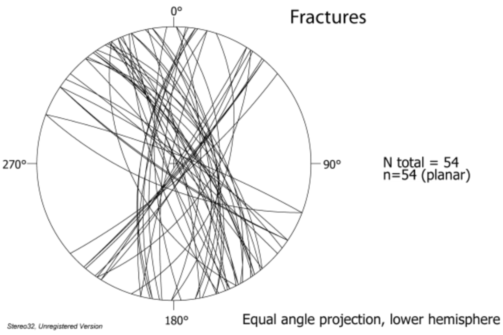


Figure 5.70C. Away from the main fault zone at Ponta das Canas, the fracturing is less intense and there is no evidence of brecciation. 2 main sets of fractures, with orientations consistent with those seen at other outcrops on the island are stained red, consistent with the red colouration of the breccia.





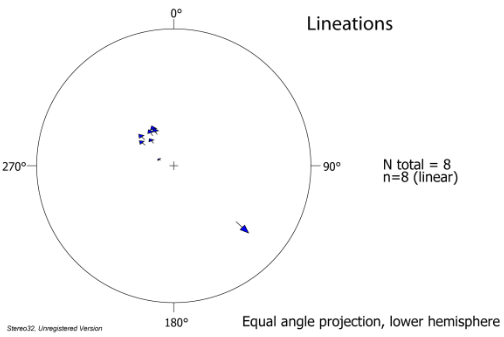


Figure 5.71. Stereonets of structural data collected at Ponta das Canas. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.6.1.4 Pantano do Sul, Florianopolis, SC

Figure 5.72 A Google earth aerial image of the outcrop at Pantano do Sul, showing the locality (yellow circle).

Continuous exposure can be found to the south of the town of Pantano do Sul, exposed at low tide across an area which is approx. 3m wide and 100m long (Fig. 5.72) A dyke at this outcrop is intruded into Neoproterozoic to early Cambrian volcaniclastic sedimentary rock (or low grade metasedimentary rock) (chapter 2.3.1.4, which is highly fractured (Fig. 5.73B). Bedding is easily observed to the north of the outcrop, away from the highly fractured region close to the dyke.

Outcrop-scale structures

This outcrop consists largely of volcaniclastic sedimentary rocks (chapter 2.3.1.4), rather than the granite which makes up most of the island of Florianopolis. The sediment appears to be a conglomerate, containing clasts of foliated material and locally folded rocks. No folding is seen in the country rock. A dolerite dyke can be seen intruding the sediments. The dyke trends NNE-SSW, parallel to the coastline and only one of its margins can be observed. It appears to have intruded along pre-existing fractures, and contains a large number of elongate xenoliths of both the volcaniclastic sediment it intrudes and granite (Fig. 5.73C). Both the dyke contacts and dominant fracture direction trend NNE-SSW (Fig. 5.74). Unusual structures crosscut the dyke, trending approximately NW-SE, oblique to the dyke trend. These structures appear to consist of multiple small joints or fractures arranged chaotically within linear zones (Fig. 5.73A). Most of the larger, more ordered cooling joints stop at these zones, although some pass through or into them. Only one fault was measured here, trending NNE-SSW, with oblique-slip slickenline lineation. This is roughly parallel to the dyke margins, which trend consistently with many other dykes observed on the island. Fractures are more scattered, with one set parallel to the dyke and fault, a few trend N-S, sub-parallel to the NNE-SSW-trending dyke. A number of fractures trend E-W, and WNW-SSE, almost perpendicular to the dyke margins (Fig. 5.74).

Interpretation

While the NNE-SSW dyke orientation is the same as others in the swarm, fracturing immediately surrounding it is more intense than can be observed elsewhere in the region, suggesting a local-scale control of the weak volcano-sedimentary country rock on the development of fracturing around the dyke. The sedimentary rocks here date from the Brasiliano orogeny, which took place 790-480Ma (Heilbron and Machado, 2003), rather than the syn-rift (Basei et al., 2008). The complex fracturing in these rocks has created smaller and more common xenoliths within the dyke that are observed at other outcrops, in Florianopolis, and across the other regions visited. This could be a function of their mechanical strength, as more fracturing would be likely if the sedimentary rocks are easier to fracture than the high grade basement. The unusual cooling joint structures within the dyke both appear to cut, and are crosscut by joints which formed during the dyke's cooling. This suggests that their formation was contemporaneous with the formation of the cooling joints within the dyke. An interpretation of these structures is difficult, as there is no reference to similar structures in the literature, either locally or in other regions.

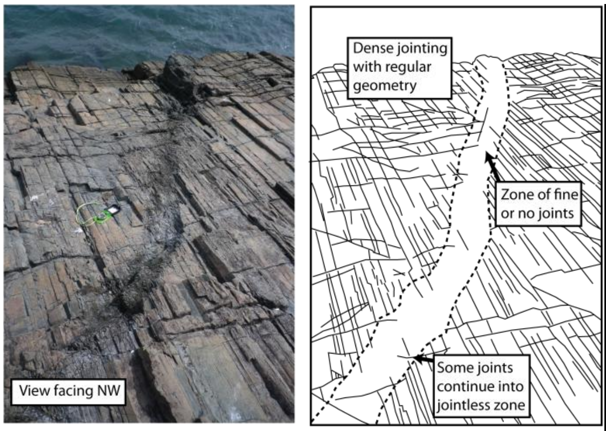


Figure 5.73A. Planar features like these, trending NNW-SSE, cut the dyke at a number of points. The majority of jointing at Pantano do Sul is very well developed on a fine scale. Some joints cut these fratures, but the majority of joints do not. The planar features themselves consist of a large number of chaotically organised joints. Features such as these are not observed at other outcrops across the area.

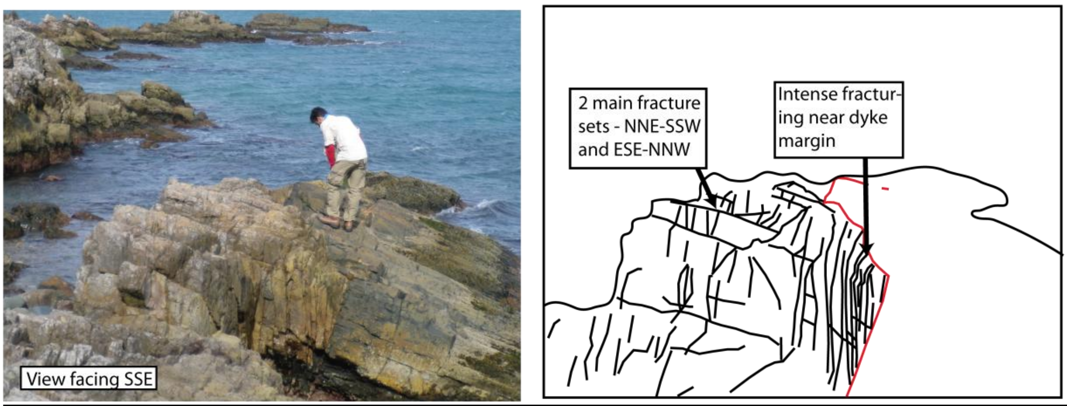


Figure 5.73B. The dyke margin, and sub-parallel fractures at Pantano do Sul. Fracturing in the volcaniclastic country rock here is much more intense than that seen at other localities.. Fractures occur in two sets, one trending NNE-SSW, roughly parallel to the dyke. The other set trends at a high angle to these, approximately WNW-ESE.

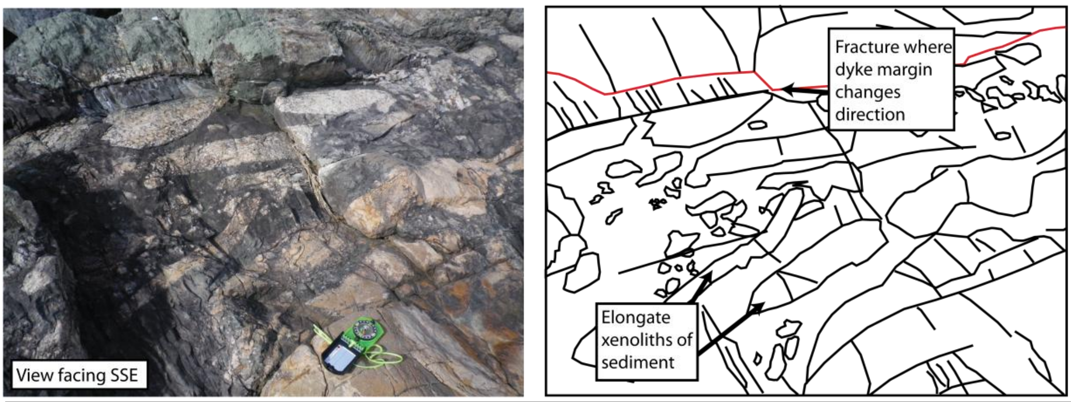


Figure 5.73C. These xenoliths form an ‘intrusion breccia’, consisting of a number of pieces of basement, with a wide array of sizes, situated around the dyke margins at Pantano do Sul. The xenoliths are tabular in shape, and oriented parallel to the dyke margins. They consist mainly of clasts of the volcaniclastics seen at this outcrop, but occasionally clasts of granite can be seen.

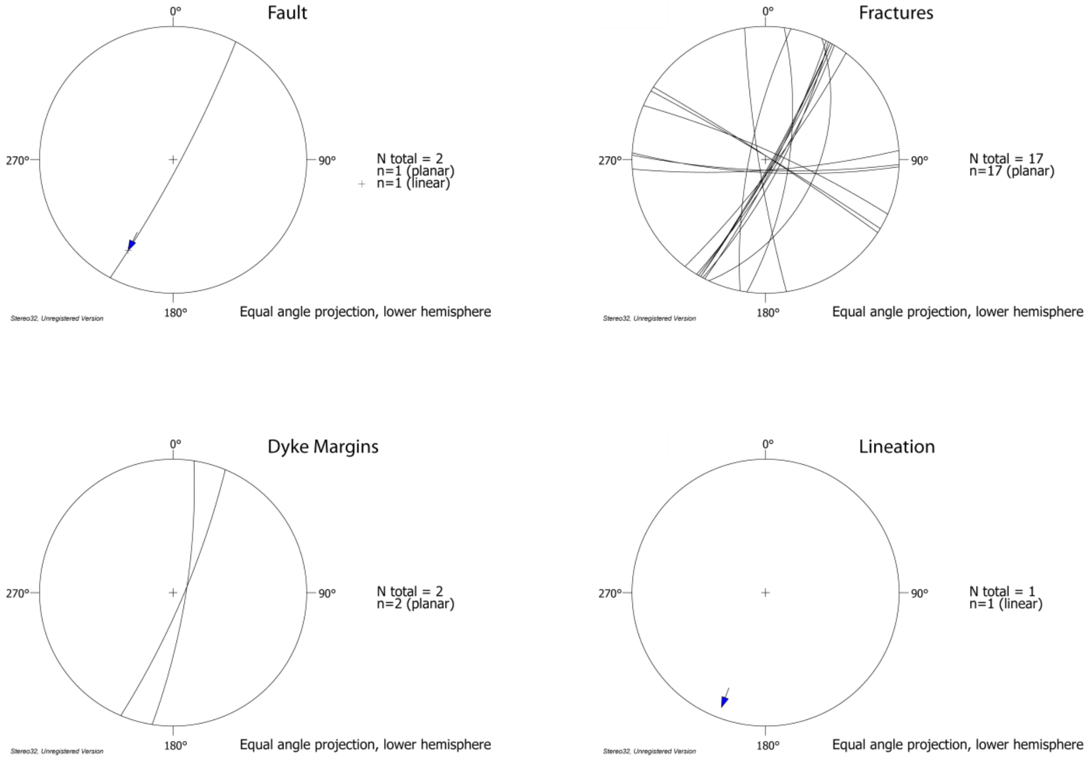


Figure 5.74. Stereonets of structural data collected at Pantano do Sul. Equal angle projections. Planes are shown as black lines, and lineations as blue arrows.

5.6.2 Florianopolis Region - Discussion and Summary

The dominant trends seen across the Florianopolis region are NNE-SSW, and NNW-SSE. As with the other regions, dykes share these trends with faults and fractures, and show evidence for having intruded along pre-existing brittle structures. Kinematic data is scarce for the region, though the large fault at Ponta das Canas shows dip-slip slickenlines.

Using the McCoss method, all of the major trends of structures observed in the Florianopolis region fit into the extensional field of transtension (Table 5.4). This is consistent with field observations of steeply plunging slickenlines (for example at Ponta das Canas), and also with the trends of structures relative to an assumed E-W regional extension direction. The table below summarises results from the Florianopolis region.

Outcrop name	Structures measured	main trend of structures	extension direction	Angle A	TT?	Field of transtension - McCoss (1986)
Florianopolis - Pantano do sul	Faults	028	090	152	Yes	General Extension
	Fractures	030	090	150	Yes	General Extension
Florianopolis - Ponta das Canas	Faults	010	090	170	Yes	General Extension
	Fractures	150	090	150	Yes	General Extension
Florianopolis - Praia Galhetas	Faults	023	090	157	Yes	General Extension
	Fractures	025	090	155	Yes	General Extension
Florianopolis - Praia Joaquina	Faults	140	090	140	Yes	General Extension
	Fractures	024	090	156	Yes	General Extension

Table 5.4 - Faults and fractures in the Florianopolis Domain, assessed for transtension using the McCoss method (McCoss, 1986). All brittle structures are transtensional, and all fall into the extension dominated field.

The key distinction between the outcrops studied at Florianopolis and those studied in the other two regions is the lack of basement foliation or structure to potentially influence the development of later fractures. Similarly to the other regions, however, complex fracture sets, and dykes apparently intruded along pre-existing fractures were observed, and the geometries of structures are consistent across all outcrops. While in the Serra do Mar region, dykes of different ages can be observed, with ages inferred based on their composition, the outcrop at Praia Joaquina preserves the first evidence for dykes cutting each other. The apparently similar compositions of these dykes could mean that they are not dissimilar in age, although it could also result from similar igneous events taking place over a long period of time. The observation that these dykes all follow fracture trends found at other outcrops in the area suggests they have been intruded after the development of the fractures. The fact that some NNW-SSE dykes cut NNE-SSW dykes, whereas the opposite can be observed to be the case at a different part of the same outcrop, highlights the complex deformation in the area. I interpret these dykes as being mutually cross-cutting and formed during the same event. If this is the case, it implies that the structures formed in a non-Andersonian style, with multiple sets of faults and fractures, with dykes infilling them. The presence of non-Andersonian structures is consistent with the regional transtension shown at all outcrops (Table 5.4).

In terms of the kinematics of the structures observed in Florianopolis, data is relatively limited. The structures are oriented closer to N-S than those observed in the other regions, and again are parallel to the regional lineament trends, highlighting the fact that the lineament analysis is likely to show brittle structures in addition to basement structures. The dip-slip kinematics observed at Ponta das Canas is consistent with the triple-junction model, with the N-S arm extending orthogonally to the E-W regional extension. Some structures at other outcrops disagree with this, however, with faults and fractures at all of the other outcrops showing lineations which plunge much more shallowly. A key distinction between the lineations at Ponta das Canas and those observed at other outcrops is the size of the structures they are associated with. The large fault at Ponta das Canas has accommodated far more deformation than the small fractures at the other outcrops. Note, however, that those structures at other outcrops can be dated relative to the dykes, whereas this fault cannot.

5.7 Summary and conclusions

5.7.1 The identification of syn-rift structures

The main syn-rift structures observed in outcrops preserved across the margin are dykes, and the faults that they intrude along. It seems unlikely that these faults are older than the earliest syn-rift (just prior to the intrusion of the dykes), as there are currently no events within the literature postulated between the end of the Brasiliano orogeny (480Ma) and the beginning of rifting (135Ma). These structures also show good geometric similarities with structures in the offshore basin (see Chapter 6) and are kinematically consistent with a regional E-W extension vector, as assumed for the region based on oceanic transform faults (Nurnberg and Muller, 1991). An important consideration when assessing the field based data is that many rift-related structures have not been sampled. Many larger structures, such as major faults may have not yet been found, or are not observed due to the thick vegetation and high weathering rates on the Brazilian margin.

5.7.2 Ground proofing of lineament trends

As described in chapter 4, it has proved difficult to directly identify specific lineaments within the area, due to the scope and scale of the study, and due to the limited exposure on the margin (see section 5.4.1.6 for description and photographs of the inland outcop at Quatis).. The geometries observed at the majority of outcrops, however, are consistent with the lineament trends of the regions in which they are found (see Chapter 7 for further discussion). This supports the view that the lineament analysis is detecting brittle structure, and that the similar lineament trends observed on either continent when Brazil and south western Africa are restored (see chapter 4) represent structures that formed during the early rift phases.

5.7.3 Kinematic Data and 3D geometry of brittle structures

Kinematic data is scarce amongst the outcrops I visited, for a number of reasons. Firstly, the majority of the structures onshore have relatively low offsets, possibly due to their location towards the edge of the main rift and also beause many larger faults are likely not exposed. Where offsets are observed, they are typically less than a few centimetres. Secondly, while many structures have undergone movement, it is often difficult to identify this in the field, due to relatively homogeneous basement, as in the case of the Florianopolis region, and some of the outcrops at Ubatuba, for example. Where fracturing is basement-parallel, offsets can only be identified on discordant basement structures which are directly cut by faults, such as pegmatites and mineral veins, yet predate rifting. Where these are not present, it is difficult to quantify any offsets, and faults have to be identified on the basis of the presence of fault rock, lineations, or both. Slickenlines and striations are not well preserved at any of the outcrops, and where they are found, steps, which would indicate offset sense, are not present, making the collection and interpretation of kinematic data difficult.

Paleo-stress analyses based on kinematic data have been used to great effect in other studies (e.g. Wilson 2005, De Paola et al, 2005), but the method is not appropriate here. The large numbers of fractures which do not have kinematic data, the lack of clear and unambiguous ages for many of the structures seen, and only relative ages where they can be identified, and the large number of post-rift events which have been identified on the margin (Ferrari, 2001; Riccomini et al., 1989) make the use of this method impractical and with considerable possibility for errors and over-interpretation.

5.7.4 The relationship between basement structures and brittle tectonics

Basement rocks across the area clearly show large degrees of heterogeneity in terms of lithology, structure, and orientation. This, together with the fact that only one outcrop shows reactivation of basement structures which do not trend NE-SW, and only a handful of others demonstrate clear evidence for basement reactivation, suggests that while preferentially oriented basement can be reactivated locally, it does not appear to exert a large control on the orientation of fractures across the area. This does not rule out the reactivation of larger basement structures as a cause for the orientation of structures on the margin, but does call into question why the NE-SW orientation of faults and fractures is so dominant in the Serra do Mar region.

If NE-SW trending, large, steeply-dipping basement structures were reactivated, forming NE-SW trending sinistral oblique faults, and brittle structures that developed within the structurally complex basement areas between them were not influenced by local basement anisotropies, then these brittle structures would be expected to trend N-S, perpendicular to regional extension vectors, and show dip-slip kinematics. This would be consistent with most models of basement influenced transtension, such as those proposed by Morley et al (2004), and McClay et al (2002), but is not seen across the Serra do Mar or Ponta Grossa domains. This hints that pervasive basement fabrics may play a role in the orientations of brittle structures, similarly to the Morley (2004) model for basement-influenced transtension. It is also possible that while reactivation was observed at many of the outcrops visited, deeper structures beneath the belt (e.g. mantle or lower crustal fabrics), do have a role in determining the orientations of these structures, though this is impossible to test.

5.7.5 Regional Conclusions

While secondary fracture orientations are commonly variable across the area, there is always a fracture set which trends parallel to the dykes. This, together with outcrop evidence of the dykes intruding along pre-existing fractures, shows that dyke and fracture orientations are closely related. Clearly, many fractures formed before the dykes intruded, showing that the controls on these fracture orientations are also the controls on the orientation of the dykes. An initial east-west extension vector, that is compatible with oblique fracturing, should lead to the formation of roughly N-S trending dykes, which can be observed in Florianopolis, but not in the Serra do Mar, or the Ponta Grossa regions. This suggests that either E-W extension was not the original vector for the Serra do Mar region, or that the dykes infilled pre-existing structures preferentially, as opposed to fracturing across or along the strongly anisotropic basement fabric. I view the latter mechanism as the more likely scenario, both given the relationship between the dykes and fractures at almost every outcrop, and the various sources of evidence showing initial opening of the south Atlantic, in the Santos basin, and other areas, was E-W oriented. These sources of evidence include the orientations of structures in basins to the North and South of the Santos basin; the orientations of oceanic fracture zones, and plate reconstructions by a variety of authors. In addition, many outcrops show sinistral kinematics on fractures which apparently predate the dykes.

Little evidence is preserved for dykes opening obliquely, i.e., basement structures are not offset by the dykes (with the exception of those at Guaratuba, which clearly intrude along pre-existing faults), and thus the individual dykes do not accommodate much oblique deformation, and are purely extensional. The en-echelon geometries and broken bridges observed are, however, consistent with the dyke swarm intruding into an obliquely deforming area. It also seems likely that the dyke swarms in three separate orientations (triple junction arms) will have accommodated extension in three distinct directions and that the faulting would then have to accommodate the remainder of the E-W extension in different ways in each region. In this heterogeneous transtension model, the faults in the Serra do Mar and Ponta Grossa regions would therefore have to extend more obliquely (sinistrally and dextrally respectively), in order to accommodate the E-W component of initial rifting compared to a homogeneous deformation. The more obliquely these faults deform, the more the regions between the dykes would have extended E-W, but narrowed in a N-S direction (Fig. 5.75). The addition of the dykes to these regions would have reduced this N-S contraction, allowing the dominant extension to be E-W. Under this scenario, both the faults and dykes in the Florianopolis region would have developed as approximately dip-slip structures, with a small oblique element.

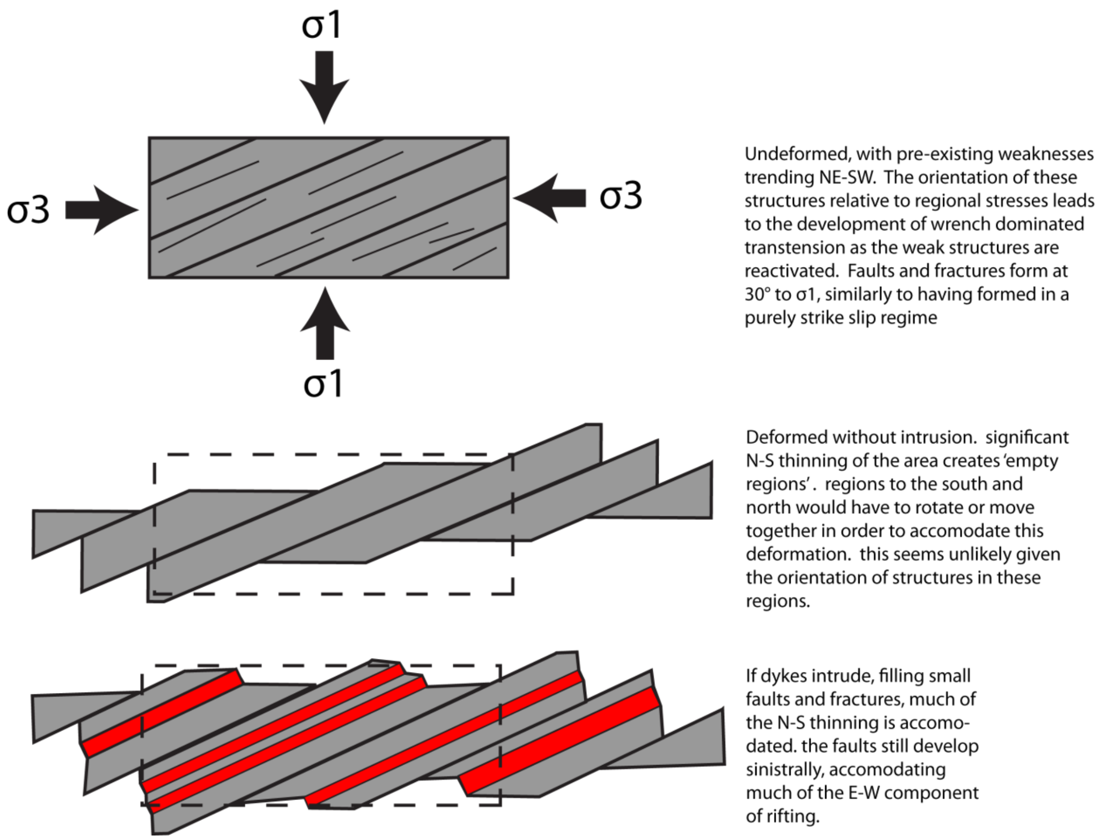


Figure 5.75. Map view diagrams (N to top of page) showing the role basement structures (thin black lines), dykes (red) and faults (thick black lines) could play in the Serra do mar region. Without dykes, significant N-S shortening would occur, whereas dykes, even though trending NE-SW, can accommodate this shortening, whilst also allowing for the same amount of extension.

This model works well to explain the oblique faulting, and integrates the igneous intrusion into the earliest rifting, particularly in the Serra do Mar region, while not requiring significant rotations of the South American plate within a short space of time, or large changes in regional extension direction during the earliest rifting, both of which have been proposed by previous authors (Stanton et al., 2010). Both are also kinematically inconsistent with the development of the three dyke swarms and their associated deformation, which occurred within a few million years of each other.

While the model proposed here accounts for how the structures behave under E-W extension, it does not explain why these structures formed in these orientations. The parallelism between basement and brittle structures seems unlikely to be coincidental. The most likely explanation is that large, weak structures, such as terrane boundaries and large-scale shear zones are likely to be the major causes of the orientation of these structures, rather than basement foliation. Where basement shear zones can be observed (Quatis for example, and a small-scale example at Guarujá), they are reactivated. Examples such as the 10m wide, unreactivated shear zone at Praia das Conchas show that high grade basement structures are unlikely to be reactivated, and that the presence of 'weak' structures is crucial for reactivation. While basement reactivation on this scale can account for the largest structures, perhaps those on the scale of faults in the offshore basin (see Chapter 6 for full discussion on these structures and their potential influences), it is not an apparent influence on the orientation on the smaller-scale structures observed at most of the outcrops in this study, nor does it appear to influence the dykes. Large basement structures, such as the CTB, and other large shear zones (chapter 2.3.2) are present in the Serra do Mar, and potentially the Florianopolis regions (large Dom Feliciano belt structures have been mapped on the island); but their presence does not explain the orientation of dykes and many fractures and faults in the Ponta Grossa region. Pre-existing structures are thought to be present here (Renne et al., 1996), although I have found no evidence for any such features, beyond the orientation of faults and dykes in the area. It is possible that if the NE-SW and N-S arms of the triple junction formed as a result of large scale basement influence, this arm formed as a means of accommodating the complex strains formed as a result of the other two triple junction arms. Examples of structures such of these can be found on oceanic triple junctions (e.g. Schouten et al (2008)).

5.8 Summary

Basement fabrics and structures typically trend NE-SW, yet display a wide array of dip angles. Despite this, faults, fractures, and dykes fall clearly into separate regions, with a dominantly NE-SW trending Serra do Mar region, NW-SE trending Ponta Grossa region, and a roughly N-S trending Florianopolis region. Fractures commonly form parallel to dykes, and many dykes appear have reactivated pre-existing brittle structures. Where observed, kinematics on faults support the 'triple junction' model, with 3 rift arms in separate orientations all formed under E-W extension. Significant uncertainty exists concerning the age of many of the fractures, since the dykes offer the only reference point. Commonly, in the Serra do Mar region, where fractures are observed crosscutting dykes, they trend NNE-SSW.

The relationship between outcrop scale structures and regional scale structures onshore and offshore is a major focus of this thesis. Large scale lineaments are described and interpreted in Chapter 4, and offshore structures are detailed in the next chapter (chapter 6). Chapter 7 compares and integrates the different datasets, to provide an onshore-offshore view of the development of rift-related structures.

6 Santos Basin Architecture and Evolution

6.1 Introduction

The lineament and field data analysis for SE Brazil presented in chapters 4 and 5 has provided a large- and small-scale view of the geometry, kinematics and potential influences on the development of brittle structures. Many of these structures formed during the pre-salt and post-rift, although due to the nature of lineament analysis, and geological fieldwork, establishing timings for these structures is difficult. To relate onshore faults, fractures, dykes and lineaments, including those seen in Africa, to the early development of the Santos basin, offshore seismic data from the whole basin was studied. The primary objective of the offshore study was to identify and map pre-salt faults (corresponding to the syn-rift and sag phases of rift development) and to compare their geometries to structures seen onshore.

Regional data for the whole Santos basin, in the form of a 2D seismic grid, spaced at approximately 2-5km has enabled the identification of large structures of a comparable scale to the larger lineaments picked from the onshore region. Image quality is unfortunately degraded by the presence of thick salt layers in the offshore basin, which dramatically reduces the clarity and resolution of the imaging of the geology below the salt.

The offshore study had three main goals:-

- To identify and map faults in the offshore basin and to enable comparison between geometries observed onshore with those mapped offshore. Horizons were also mapped, to gain understanding of their morphologies during and after the pre-salt period.
- To identify timing of formation and activity on structures, relate these events to structures of known age onshore, and to broaden the understanding of the timings of structural development onshore. This would be achieved by identifying geometries and kinematics of structures of known age offshore, and comparing these to outcrop and lineament data onshore.
- To assess the presence and role of hypothesised transfer zones within the offshore basin and to determine whether these structures are hard or soft linked and whether they correlate with structures onshore, and magnetic and gravity anomalies offshore.

6.2 Methodological considerations

The seismic datasets made available to this study by BP comprised an extensive 2D survey across the entire basin that was acquired by BP from a number of sources. Two 3D seismic cubes owned by PGS (bzpgs_m) and CGG (bzpsalt) were also made available (Fig. 6.1). 2D surveys are collected and processed as individual lines, or multiple lines in a grid, whereas 3D surveys are collected and processed as volumes, and allow much better data resolution and more interpretation options (Kearey et al., 2009).

The 2D dataset consists of a number of 2D lines throughout the Santos basin (Fig. 6.1). These lines were acquired by BP from a variety of sources, and largely consist of 100's of km long regional lines, in a grid which covers the entire basin. Grid spacing varies depending on the location of the lines, and the original survey which was collected. In general, grid spacing is closer in the northeast of the basin, and wider in the southwest. All lines were time migrated, although the diverse sources and ages of the lines led to variable data quality, particularly beneath the salt.

The higher resolution 3D seismic data provide a better understanding of how to interpret the 2D data, and allow identification of smaller-scale, more complex structure (Fig. 6.3). Two 3D surveys, in the eastern region of the basin were available (Fig. 6.1). These data allowed the identification of faults offsetting both pre-salt and sag sediments (the criteria for the identification of these structures will be discussed later in this chapter), and the interpretation of the top of the basement, marked by the lowermost continuous reflectors in the pre-salt sediments. These geometries and horizons were then applied to the regional scale 2D data to extend coverage across the basin, allowing a more educated interpretation of structures in the 2D data than could be achieved without the higher resolution 3D data. A summary of the key acquisition parameters is presented in table 6.2.

Survey Name	**Bzpgs_m**	**Bzpsalt**
Approx. Survey Size	5,670Km^2	18.850Km^2
Streamer Length	6000m	6000m
Number of Hydrophones	600	480
Group Spacing	10m	12.5m
Migration Technique	Kirchhoff PSTM with ray bending, high order NMO	Kirchhoff PSTM
Bin Size	6.25 m x 25 m	37.5 x 6.35 m
Fold	60	60

Table 6.2 – Acquisition Parameters of the 3D seismic Surveys

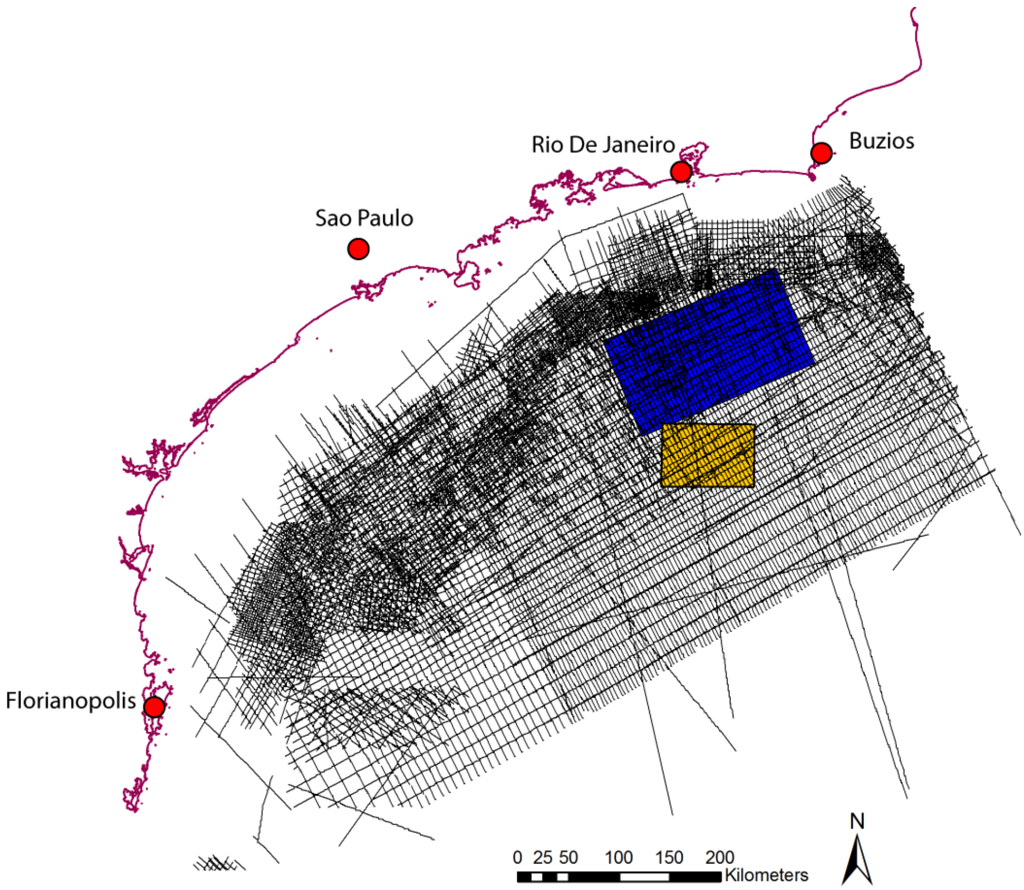


Figure 6.1. Locations of available seismic data from the Santos Basin. 2D surveys (Black Lines) cover the entire basin with varying data density. 3D surveys are located in the northeast of the basin. Bzpgs_m is coloured yellow, and bzpsalt is coloured blue.

2D seismic data is strongly dependent on its orientation, both in its processing and its interpretation, as seismic waves travel at different velocities depending on the orientation of the rocks they are travelling through (Kearey et al., 2009). This is clearly important in areas of complex deformation, or where rocks are strongly anisotropic. When interpreting structure on 2D datasets, faults which are parallel to the lines will not appear on those lines, and faults with limited extent may not appear on many lines depending on the line spacing, and so may be difficult to interpret as 3D structures. If a fault is only seen on one seismic line, it is very difficult to interpret its orientation, as the line may be oblique to the trend of the fault.

Wells are commonly used to identify specific stratigraphy in offshore basins, and their presence can be invaluable to the interpretation and understanding of complex stratigraphy. While numerous wells had been drilled in the basin at the time of interpretation, data from these wells are confidential, and therefore no sub-salt wells were available to aid my interpretation of the offshore data. Interpretations were therefore largely based on consistent geometries of faults and horizons across different seismic lines and, where applicable, amplitudes of seismic reflectors across the basin. The interpretation of areas further from the clearer 3D data is based largely on extrapolation of these horizons and therefore is less reliable than the mapping within the 3D volumes, and in regions where salt has withdrawn.

This study focuses on the syn-rift part of the Santos basin and it is likely that in this part of the section, basement rocks will be juxtaposed against sediments in the earliest faults. The syn-rift is likely to have developed as a series of tilted fault block half-grabens, into which the earliest continental and lacustrine sediments form and are thought to be the source rocks for the pre-salt hydrocarbons in the basin.

Although interpretation of 2D data was possible across much of the basin, it was often difficult to identify faults, in particular those which juxtapose sedimentary and basement rocks. In addition, basement rocks, which are overlain by volcanics are, like salt, difficult to image using conventional seismic methods, and therefore do not tend to form easy to interpret reflectors and therefore interpreting faults entirely within basement is not possible.

6.2.1 The effect of salt on seismic interpretation.

When compared with typical clastic or carbonate sediments, salt has a very high seismic velocity. This means that seismic waves travel much faster through the salt than they will through typical sediments. This can cause waves to be scattered, making imaging beneath salt difficult (Kearey et al., 2009). Where salt is strongly heterogeneous, this effect can be compounded by a lack of understanding of its internal structure. In addition to this, salt is very mobile in the subsurface, typically forming large diapirs, and completely withdrawing from other areas. These changes in structure and thickness can make imaging beneath it challenging. The increased seismic velocity through salt also leads to a ‘pull up’ effect, as the faster seismic waves arrive at the receiver more quickly, and two-way travel time is reduced.

On recent surveys, such as the 3D surveys I interpreted, the data have been migrated to account for the salt, allowing for improved sub-salt imagery. On many of the 2D surveys, which were collected and processed less recently than the 3D surveys, this type of migration has not been done, and so interpreting data from beneath the salt proved more challenging. Some regions, in particular those in which salt has withdrawn or is thinner, allow structural interpretation, however, this is much more difficult in areas with thick or heterogeneous salt.

6.2.2 Which horizons were picked?

The top of the basement was picked as offsets of this horizon relate to faults that may have been active during the earliest rift, and possibly relate to the structures seen onshore. Picking this horizon proved difficult due to the lack of a continuous reflector separating basement and sediments. This is a relatively common feature of seismic data from the Santos basin, and has led some authors to avoid interpretation of this horizon (Guerra and Underhill, 2012). In this study, the 'basement' horizon I have picked is really the 'acoustic basement' i.e. the horizon beneath which no reflections that can be interpreted. I treat this as a proxy for crystalline basement as it can be clearly distinguished from syn-rift sediments in the inboard regions, where pre-salt data quality is higher. Basement structures, such as large shear zones, or smaller scale features such as basement foliation cannot be imaged in these data, and therefore identification of basement reactivation or influence is impossible, since identification of this relies on a clear visualisation of the relationship between basement structures (and fabrics), and later brittle structures, such as faults and dykes. In places, high amplitude reflectors, perhaps representing the tops of lava flows (lava flows make up some of the earliest stratigraphy in the basin, and are therefore likely to lie directly on basement - see chapter 2.5.1) could be identified although in general, basement was characterised by its lack of continuous reflectors. Due to the absence of a high amplitude basement reflector, the lowermost sedimentary reflector was picked, and therefore this 'top basement' reflector may be better termed 'base pre-salt'.

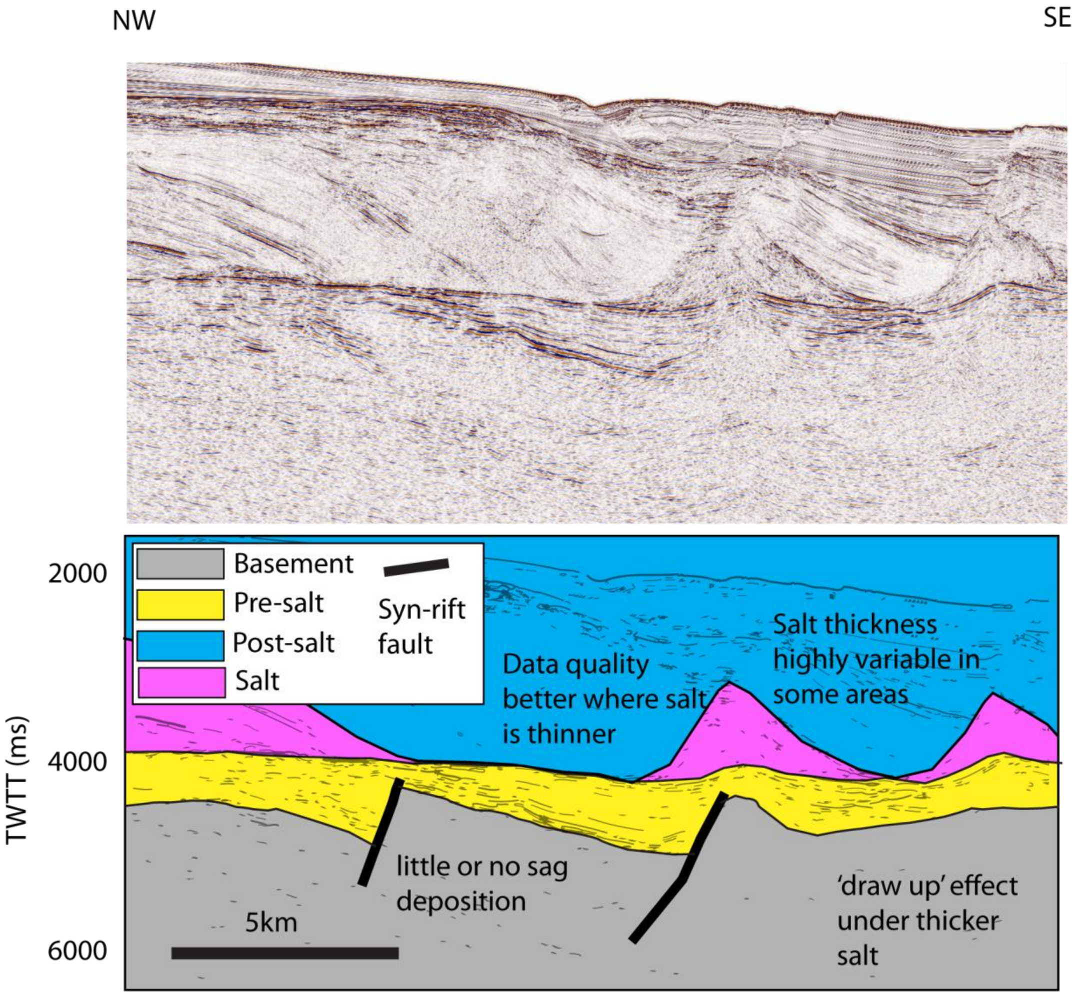


Figure 6.2 – a pre-salt tilted fault block, well imaged on 2D seismic data due to relatively thin salt in the 'Albian Gap'. These tilted fault block structures are the main focus of the study. Top-basement is identified just below the lowermost consistent reflectors that can be identified. Faults are identified based on the geometries of tilted fault block structures such as these, although variable sub-salt data quality in the 2D seismic surveys means tilted fault block structures are rarely as clear as this. Data examples courtesy of the WesternGeco/TGS Brazil Data Alliance.

The base of the salt was the other major reflector picked, as it represents the end of the rift-sag phase of margin evolution, and because the interest of the study was in the pre-salt. It is typically seen as a high amplitude reflector, and other than being cut by faults in some parts of the basin, which will be discussed later, it is relatively continuous across the area. Due to the low resolution of most of the 2D data, and some regions of the 3D data, and due to the timescale imposed by the regional nature of the study, it was not possible to pick horizons from within the pre-salt that would be continuous or meaningful across the area.

6.2.3 Criteria for picking faults

Since the objective of the offshore study is the identification and interpretation of faults in the basin, it was important to be consistent when picking them. In both 2D and 3D seismic data, faults are picked as segments on a seismic line and then multiple segments are linked to form a fault surface. A variety of different factors and possibilities need to be considered when picking each fault segment. As previously mentioned, the majority of faults picked, especially the earliest pre-salt faults juxtapose seismically anisotropic basement and sedimentary rocks. Many of these faults will have become inactive during the deposition of the sedimentary sequence, and therefore the basement fault block will be covered with sediment which shows no offset, masking evidence of earlier faulting. Similarly, sedimentary rocks may onlap onto basement topographic highs, which may give the appearance of faulting when it may not (or may) have taken place. Areas without reflectors may be seismically isotropic basement, or they may simply be areas where data quality is low due to overlying salt, and therefore the presence of sediment juxtaposed against regions with no seismic reflectors is not conclusive evidence for the presence of basement highs or other seismically isotropic features.

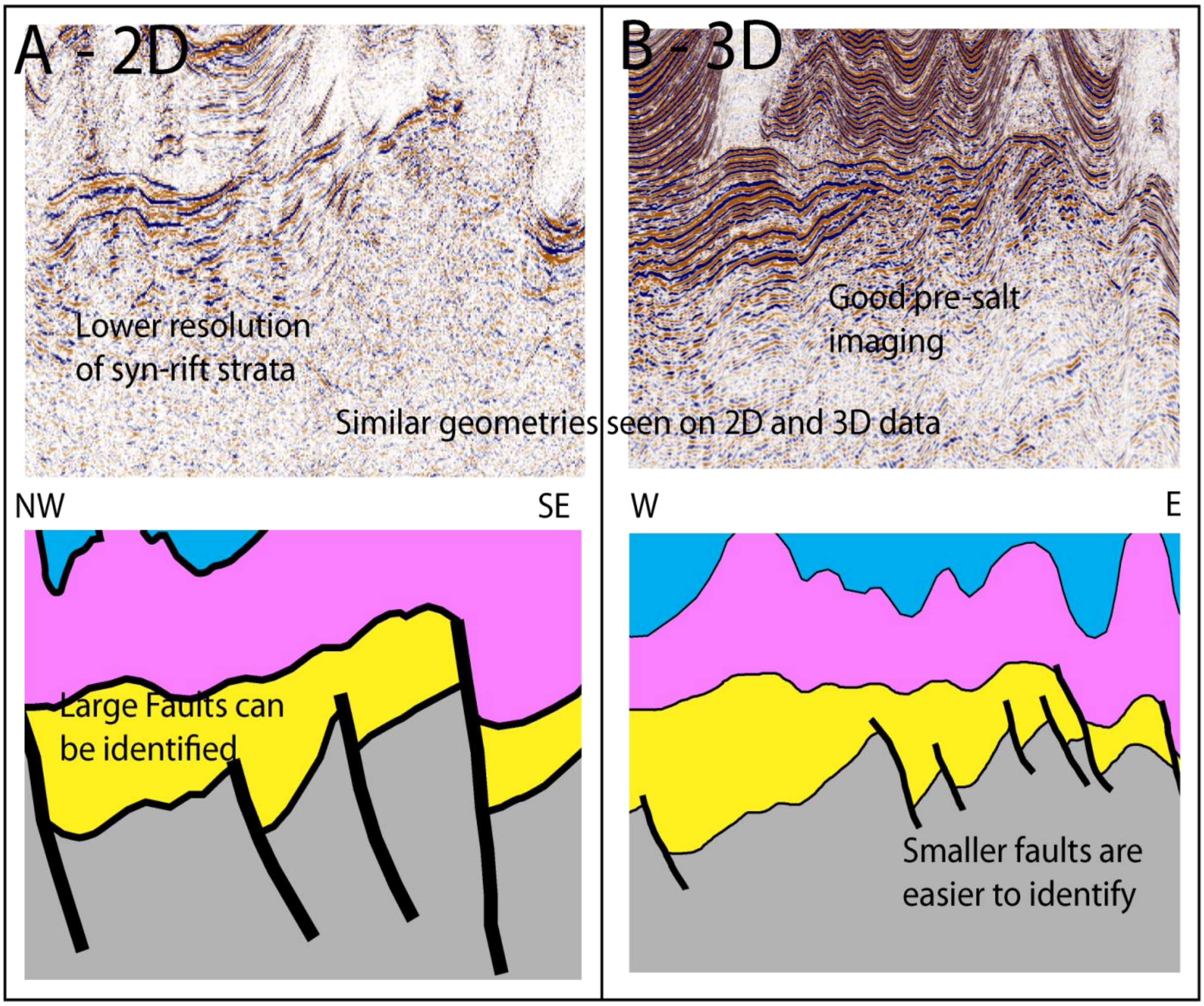


Figure 6.3 – Sections of 2D (A) and 3D (B) Seismic data, showing the same structure (see figure 6.6 for further detail). This image highlights how local 3D seismic data was used to guide the interpretation of the regional 2D surveys, which suffer from poor sub-salt imagery. Smaller structures can be identified using 3D data, but their geometries are similar to those observed using 2D seismic. A) Data examples courtesy of the WesternGeco/TGS Brazil Data Alliance.

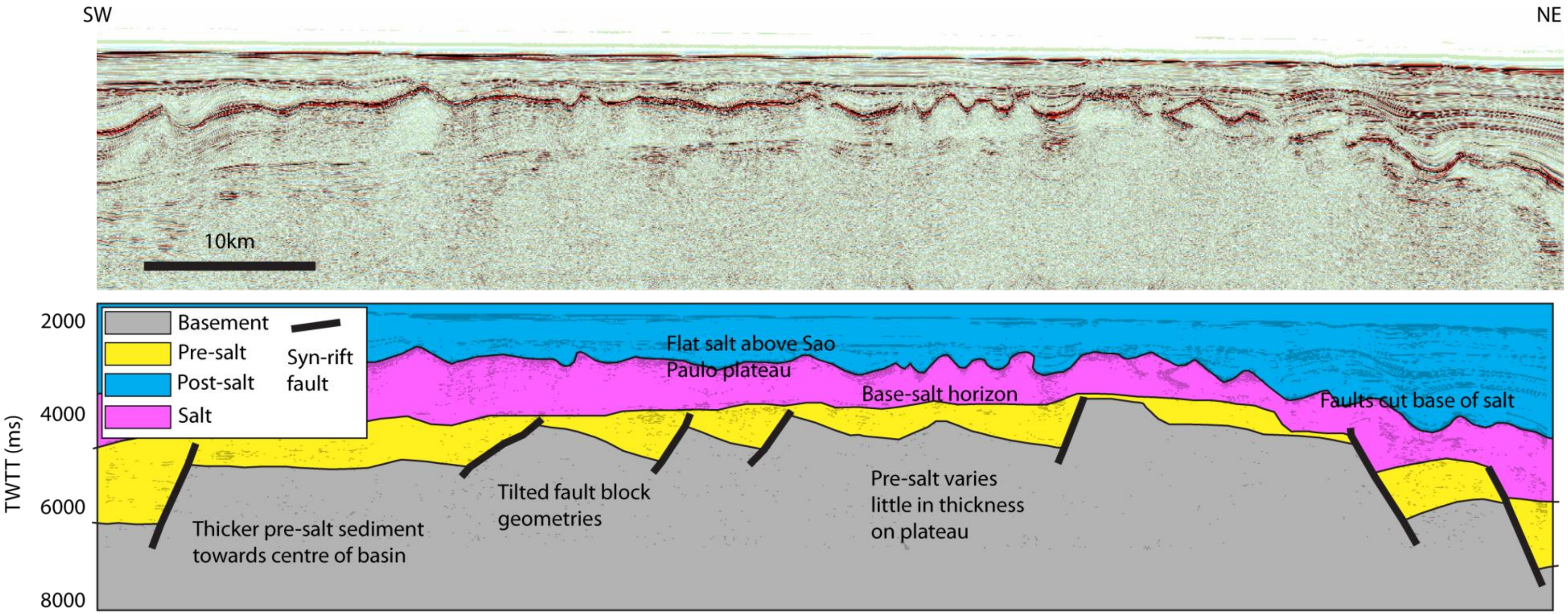


Figure 6.4 – A regional view of the pre-salt rocks on the São Paulo plateau; the high region in the centre of the image. The pre-salt rocks vary little in thickness on the plateau, but thicken at either side, suggesting the plateau played a role in governing how and where sediment was deposited during the early rift. On the plateau, some tilted fault blocks almost reach the base of the salt, whereas to its eastern edge, many faults cut the base of the salt. Sub-salt data quality such as this is typical for much of the 2D data, and requires careful interpretation. Data examples courtesy of the WesternGeco/TGS Brazil Data Alliance.

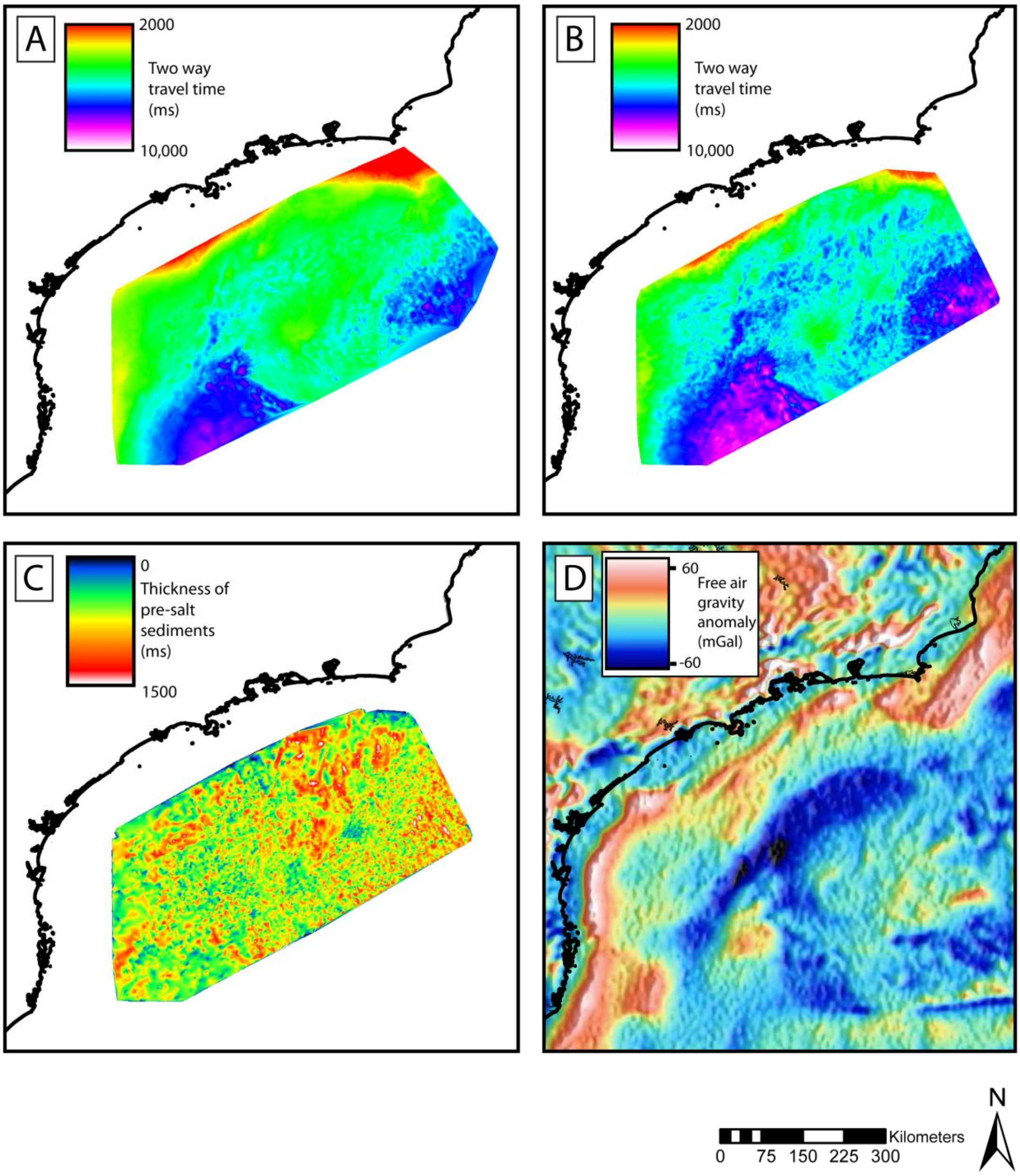


Figure 6.5 – Maps of base salt (A), top-basement (B), pre-salt thickness (C), and free air gravity from the Santos basin (D), after Sandwell and Smith (2009). The broad high in both the base of the salt and the top of the basement is the São Paulo plateau. The deep region to the southwest of the basin is thought to be the location of an incipient ocean spreading centre (Scotchman et al., 2010). This region is also the location of a large number of faults which appear to cut the base of the salt (see Figure 6.6). Other than in this region, the deepest top basement picks inboard of the São Paulo plateau correspond with a low gravity anomaly, and are consistent with thick sediment (parts B, C and D). The thickest pre-salt sediments are found to the east of the basin, although the thickness of this interval is relatively consistent, other than the local changes related to individual fault blocks.

6.3 Data interpretation and analysis

6.3.1 Regional scale geometries and structures

6.3.1.1 Top-basement

The most obvious features, when looking at the top-basement horizon are the deep low in the southwest of the basin, and the broad high in the southeast (Fig 6.5). The broad high in the centre of the basin is the São Paulo plateau (Fig 6.5). The syn-rift of the sao Paulo plateau comprises a series of small tilted fault blocks, blanketed by parallel layers of sedimentary rocks.

A deep region to the southwest of the basin is the location of a failed ocean spreading ridge hypothesised by previous authors (Scotchman et al., 2010). Towards the coastline, the top-basement horizon shallows gently, until it can no longer be traced. This may be due to the Cretaceous ‘hinge zone’ (see Chapter 2). No evidence for large scale faults can be seen in these data, suggesting that the hinge zone may not have been defined by faulting during the syn-rift. Sediments beneath the salt are of a relatively constant thickness, averaging around 750ms TWTT (although local variations due to deposition in half grabens can be observed).

The 3D surveys highlight the small scale basins that take the form of tilted block half grabens (Fig. 6.6). The relatively constant thickness of pre-salt sediments suggests that the early subsidence and extension in the basin was evenly distributed across most of the area.

6.3.1.2 Base-salt

The base-salt horizon appears to broadly follow the same large-scale features as the basement horizon, i.e. the Sao Paulo plateau and the deep region in the centre of the basin. These regions presumably formed topographic features during the sag and salt deposition phases of basin evolution. Salt appears to be absent in the deep part of the basin, possibly because seawater was too deep to allow evaporation and salt deposition in this area. The ‘Albian gap’ is a well documented region where salt has withdrawn completely (Modica and Brush, 2004), allowing better visualisation of structures beneath it. In this region, a high amplitude reflector similar to the base salt reflector can still be seen, possibly as a result of remnant salt left after withdrawal (Fig. 6.2). This high amplitude reflector was picked as the base-salt in this region, as it defines the uppermost pre-drift sediments. In most places, the base of the salt lies conformably on the sag horizons, reflecting the relatively even subsidence of the central basin. In the region to the east of the Sao Paulo plateau, evidence for localised erosion of strata before sag deposition can be seen, with the base of the salt lying unconformably on eroded strata (Fig. 6.6). This indicates shallow or sub-aerial exposure during the period before the sag, which is consistent with the literature concerning the sedimentology of the basin (Contreras et al., 2010; Karner and Gamboa, 2007), which suggests that this area was raised high prior to salt deposition. Some faults can be seen to cut the base of the salt, particularly around the area where erosion of strata appears to have taken place (Fig. 6.6). I interpret this as suggesting that the São Paulo plateau was a structural high during the sag, before the base of salt. The raised region can also be clearly identified in the base salt horizon, suggesting that this high remained throughout the pre-breakup period.

6.3.2 Faults

In the north of the basin, faults trend NE-SW, approximately parallel to basement structures onshore, as well as dykes and faults mapped in the Serra do Mar region (see chapter 5). In the centre of the basin, faults mapped on both 2D and 3D data trend NNE-SSW (Figs 6.7A and B). On the 2D data, no evidence for hard linked transfer zones, as proposed by many authors (Meisling et al., 2001; Franco-Magalhaes et al., 2010) was observed although changes in fault polarity may suggest soft-linked structures (Fig. 6.7) could define these features.

The majority of faults do not cut up through the sag horizons that formed largely due to thermal subsidence in the basin. This may be interpreted that syn-rift faulting was relatively short lived but took place over a broad area. This observation of initially wide rifting localising to a smaller number of dominant structures could be considered consistent with models for fault propagation and basin evolution, but needs further evidence to test this hypothesis. Under these models (Cowie et al., 2000; Gawthorpe and Leeder, 2000), larger structures form by the linkage of smaller faults along strike. In the 3D seismic data, some evidence for this can be seen, although even in the 3D surveys, data resolution and clarity are not sufficient to accurately identify fault throw profiles, or small fault tips, which could be used to confirm this idea.

A small number of structures can be seen to cut the sag horizons and the base of the salt, in both the 3D and the 2D data (Figs 6.3, 6.4 and 6.6). To the east of the basin, these faults correspond to an 'outer hinge' e.g. Karner and Driscoll (1999). Towards the centre of the basin, faults can also be seen to cut the sag and base of the salt, forming the western edge of the São Paulo plateau, and separating this uplifted region from the deeper southwest part of the basin, and defining an 'inner hinge' (Fis 6.4 and 6.7A). In contrast to the diffuse faulting pattern that formed the earliest pre-salt structures, these base-salt-cutting faults are located in two regions to the centre and far eastern part of the basin (Fig. 6.7A). These faults displace the base of the salt by similar amounts to the size of the initial displacements which formed the syn-rift half-grabens (<500mstwtt), suggesting that their activity following the formation of the initial half grabens was significant. In the centre of the basin, these faults consistently trend NNE-SSW. This indicates a change in regional deformation style, from NE-SW oriented faulting, to NNE-SSW oriented faulting following the earliest rift. Towards the eastern edge of the basin, faults which crosscut the base of the salt trend NE-SW, parallel to structures onshore, and to the NE-SW faults in the north of the basin (Fig. 6.7A).

Whether or not the faults that cut through the sag were active during the deposition of the salt is clearly a key piece of information that needs to be established when trying to understand the evolution of the basin. A key problem with these structures cutting the base of the salt is correctly identifying timings of fault activity. These structures may have been inactive, simply forming highs onto which sag sediments and evaporites were deposited; or they may have been active structures that these sediments covered, becoming inactive shortly after, or during the deposition of the sag. The presence of these relatively large offset structures is inconsistent with the diffuse, low offset nature of the pre-salt structures that can be identified, and it is consistent with localisation of deformation during rifting. Some structures show evidence for erosion prior to the deposition of the salt, suggesting that they were sub-aerial at the time (Fig. 6.6). Other structures show no such evidence, suggesting they were not in an erosive environment at any point prior to the deposition of the salt. The data are clearly difficult to interpret, however, the fact that these faults are continuation of pre-salt structures, which appear to cut both the sag and the base of the salt is compelling evidence that these structures were either active throughout, or the majority of the sag and the early salt deposition. The faults also had sufficiently large offsets to form local highs throughout the pre-salt, and into the deposition of the salt.

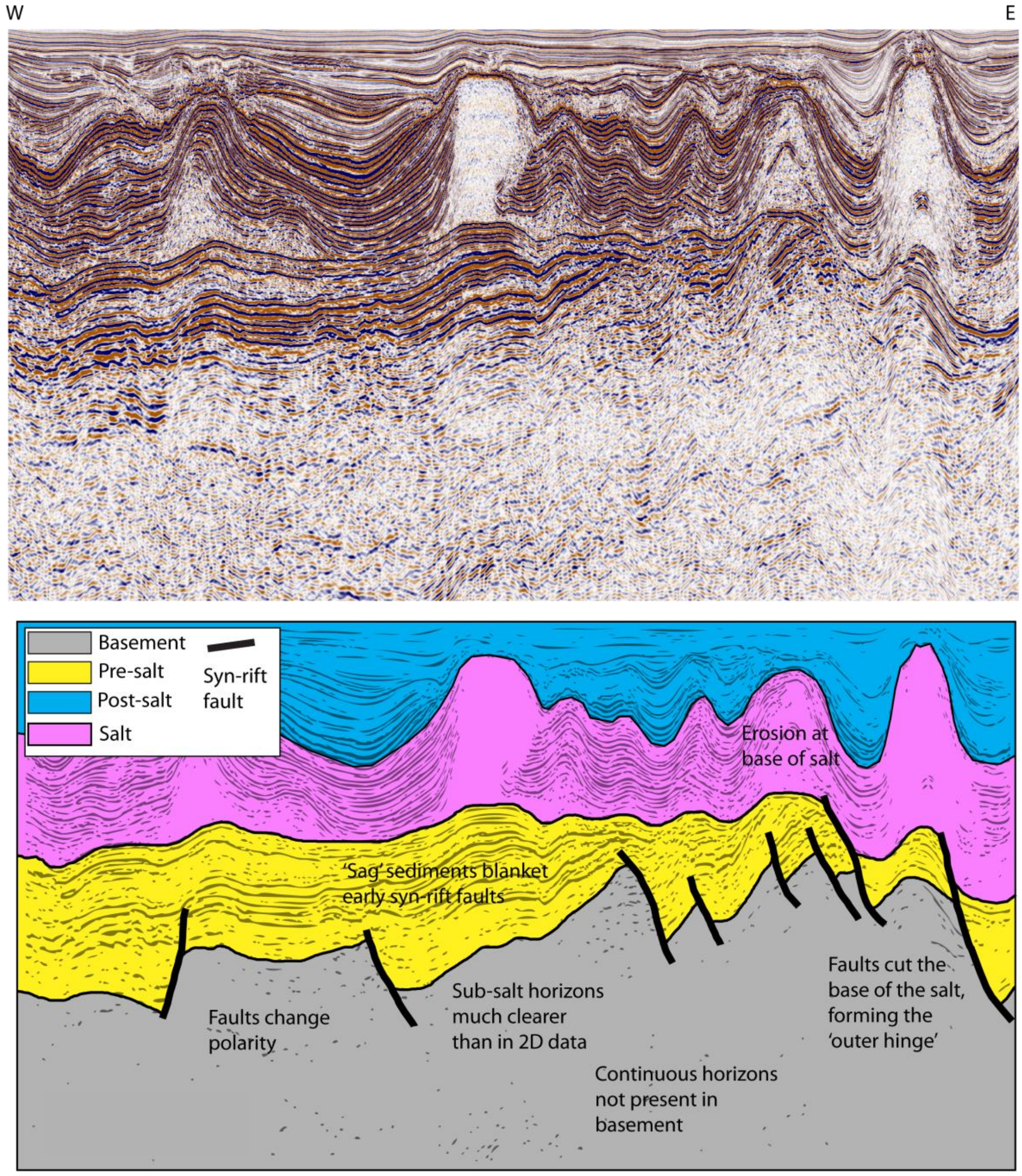


Figure 6.6. The 'outer hinge' in a line through the 3D seismic data. The 3D data typically offers higher quality imaging in the sub-salt section and much higher spatial resolution. Many more faults can be picked in this data than the 2D data and correlating structures between lines is easier. To the W, tilted fault blocks are seen in the basement immediately beneath the base of the salt. The presence of truncated syn-rift reflectors beneath the salt is good evidence for the basement having been sub-aerially exposed and eroded prior to the deposition of the salt. To the west towards the centre of the basin, faults are blanketed by a layer of sediments, with a relatively consistent thickness. These sediments are the sag horizons, deposited during thermal subsidence of the basin. Image is approx 35km wide, with approx. 6s TWTT vertical extent. Data Courtesy of CGG

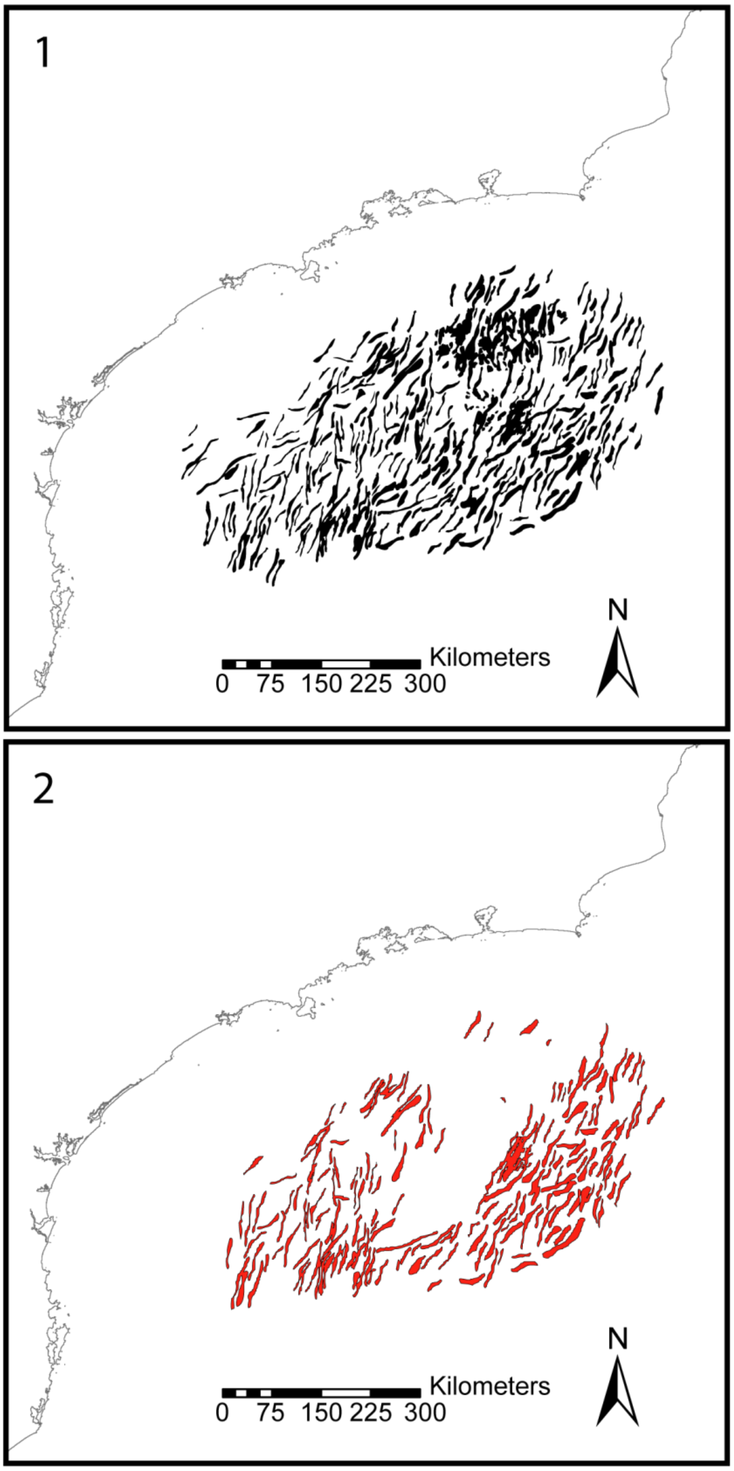


Figure 6.7A. The locations of all faults mapped in the offshore basin cutting Top Basement (part 1) and Base-salt (part 2). The faults cutting the base of the salt fall into two regions: a region containing dominantly NNE-SSW trending structures to the southeast of the basin, and a region containing dominantly N-S trending structures in the centre of the basin. The region to the east of the basin eventually became the Atlantic Ocean, whereas the region to the centre of the basin may have been the location of an incipient spreading centre, after Scotchman et al (2010).

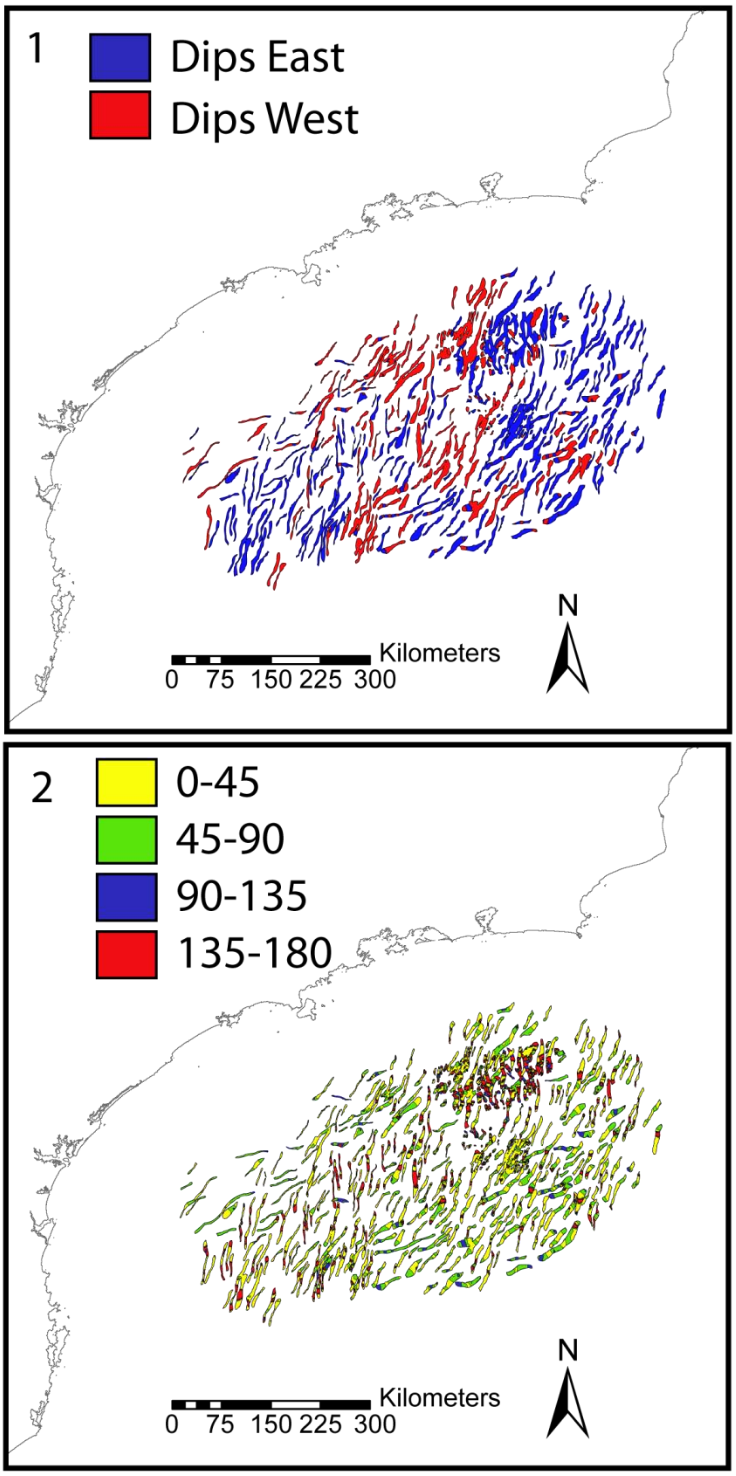


Figure 6.7B. Faults mapped in the offshore basin cutting Top Basement, coloured by Dip direction (part 1) and Strike Direction (part 2). Part 1 shows evidence of compartmentalisation of dip azimuth into dominantly East dipping and West dipping domains, which could be considered evidence for soft-linked transfer zones. Part 2 show strike in 45° Bins. The regions to the southeast and northwest of the basin show dominantly NE-SW (green and yellow) strikes, whereas the region in the centre of the basin shows more N-S trending faults (red colours).

6.3.2.1 Basement influence?

A primary aim of this study is to try to understand the geological links between the onshore geology of SE Brazil and the offshore Santos basin. The large distances between the offshore and onshore regions, together with the strongly heterogeneous basement seen onshore may mean that any information from the onshore may not apply well to the offshore basin, as continuity of structures and fabrics cannot be assumed. Nonetheless, in terms of the geometry and orientations of the structures, the parallelism between the NE-SW faults in the north of the Santos basin and structures in the Serra do Mar region; and the parallelism between the NNE-SSW trend of structures in the west and centre of the basin, and many structures seen in the Florianopolis region, are striking. These structural trends can be observed onshore Brazil, both in lineament analysis and field data, and on the African margin, highlighting that they were clearly important before margin break-up. It is my interpretation that the potential influences on the geometries of these structures are likely to be the same as the influences on the geometry of structures onshore. I consider it to be unlikely that the similarities between the trends of lineaments onshore, faults and dykes seen at outcrop scale, and the orientation of faults in the offshore basin, are coincidental. See chapter 5 for further discussion on the potential influences of structures onshore. The 2D and 3D seismic data have enabled construction of regional scale fault maps, however the resolution and quality of offshore sub-salt seismic data is not, at the time of interpretation, sufficient to use to map basement structure or fabrics. This means that basement reactivation or influence cannot be assessed using the seismic data for the Santos basin, other than by comparing the timings and geometries seen with those onshore. Thus understanding the onshore rifting, both on large and small scales, is crucial when interpreting the data offshore. This will be discussed further in chapter 7.

6.3.2.2 Hyperextension and asymmetry

As discussed in chapters 2 and 3, many authors have proposed that the Santos basin is a hyperextended continental margin, with two main models proposed to explain the high degrees of extension and crustal thinning. Since neither low angle detachment faults, nor faults that have been rotated prior to being crosscut by later faults, were identified on the 2D or 3D seismic data, it is difficult to support either model. Below the top basement reflector, which is itself faint and difficult to follow in places, interpretable data is either absent or clouded by multiples of the seabed, and the top of the salt in places, for structures to be picked. The strong asymmetry between the Santos basin and those basins on the Namibian margin is supportive of the detachment model, with the Sao Paulo plateau forming the ‘H Block’ or ‘continental ribbon’, as proposed by Lavier and Manatschal (2006). However, if the deep region to the southwest of the basin is a failed ocean spreading centre, the situation is more complex, as large, low angle detachments clearly do not underly the whole basin. The basin could in fact be treated as two distinct rifts; one which eventually formed the South Atlantic, and the other, which is a failed rift, separating the Sao Paulo plateau from the western side of the basin. If the Santos basin were to be interpreted as two separate rifts, and ocean spreading was assumed to have initiated in the centre of the basin, the presence of oceanic crust would clearly have implications for how the position of the ocean continent boundary is defined. The heterogeneous extension and thinning associated with the local formation of an oceanic spreading centre would also affect estimations of extension factors, as the whole basin could no longer be treated as a single piece of thinned continental crust..

6.3.2.3 Transfer Zones

Many previous authors have suggested that transfer zones segment the offshore basin. These studies often disagree on the number of transfer zones, their extent, and whether they can be linked with onshore features (de Souza et al., 2009; Franco-Magalhaes et al., 2010; Meisling et al., 2001). Studies commonly propose these are hard linked faults, accommodating much of the dextral component of rifting, and representing the offshore effects of the Ponta-Grossa deformation. A common weakness of these studies is that they commonly use relatively limited amounts of 2D seismic data from the basin, often restricted to certain regions, and often only consisting of a few lines in the same orientation. This makes the interpretation of faults difficult, as it is impossible to correctly identify the trends of structures based on this limited data. See discussion in Section 2.5.2.

Using 2D seismic for the whole basin, and the 3D data cubes has enabled a critical examination of these potential transfer structures across the entire basin. No evidence for hard linked structures that trend in the same orientation as the purported transfer zones was observed, suggesting that transfer faults in the Santos basin are not as common as previous authors have suggested.

Despite evidence for ‘Hard linked’ structures, the dip polarities of faults in the basin suggest that smaller-scale soft linked transfer zones may be present. By plotting fault dip azimuths on the structures themselves, and colouring faults which dip towards 0-180 blue, and those which dip towards 180-360 red, I have separated eastward dipping (synthetic) and westward dipping (antithetic) faults (Figure 6.7B). Compartmentalisation into zones where faults have a similar dip polarity is apparent within the basin. The edges of these zones appear to trend NW-SE, supporting the view that transfer zones do segment the faults in the offshore basin. These structures, if real, appear to have played a key role in the earliest rift, although they are not observed as cutting the base of the salt to the same extent.

Soft-linked ’transfer zones’ were mostly observed in the 2D seismic and therefore should not be considered as being real structures, due to large areas where data interpretation was hampered by the effect of thick salt on the seismic data. The orientation and location of these putative structures would agree with many published papers concerning the offshore basin, and they do share similar orientations with structures seen onshore across the area.

The zones of faults with different dip polarities also do not appear to line up well with geophysical anomalies from the offshore basin (Fig. 6.5D and Figure 6.7A). When compared with geophysical data, and with interpretations of transfer zones by previous authors (de Souza et al., 2009; Meisling et al., 2001), it is clear there are significant differences between my interpretations and previous work. Based on this study, whilst I do see evidence for fault polarity changes, it is difficult to support any of the existing models for transfer zones in the Santos basin

6.3.2.4 Other compartmentalisation

As previously mentioned in section 6.3.2, faults in the northeast and southwest parts of the basin trend closer to NE-SW than those in the centre of the basin, which trend NNE-SSW to N-S. The NNE-SSW and N-S orientations of the faults in the centre of the basin correlate with the orientation of the Florianopolis dyke swarm to the west (Chapter 2.4.1.1), and are similar in orientation to structures such as the fault seen at Ponta das Canas to the north of Florianopolis (Chapter 5.6.1.3). The NNE-SSW-trending faults also share an orientation with lineaments mapped in Angola and Namibia (Chapter 4.5) although this geometric correlation is less clear than the correlation with structures on the Brazilian margin (see chapters 4 and 7 for further discussion concerning these correlations). The NE-SW faults in the north of the basin are possibly controlled by the same influences as those in the Serra do Mar region. If this was the case, they would have formed in a wrench-dominated setting, with dykes possibly accommodating N-S extension. The region of N-S faulting in the centre of the basin, to the North of the Sao Paulo Plateau (Fig. 6.7A) is coincident with a large negative gravity anomaly (Fig. 6.5D), and also some of the deepest top-basement reflectors picked (Fig. 6.5B, other than those in the large trough to the south of the basin (Fig. 6.5A). Due to its low density when compared to crustal rocks, thick sediment is likely to be responsible for this gravity anomaly, suggesting that the extension dominated faults led to much more deepening in the centre of the basin, and therefore more accommodation space for sediment. This fits well with a model for extension dominated transtension, where the main shortening direction is vertical (Chapter 3.2), leading to the formation of deeper basins. In contrast, the Serra do mar region, appears to be wrench dominated, and therefore would have a N-S (as opposed to vertical) shortening direction (Chapter 3.2), and therefore thicker crust. Much of this N-S shortening is likely to have been compensated for by dyke intrusion - see chapter 5.7)). Sediment is less thick in the wrench dominated regions, and in the onshore region, where the basement is probably thicker, accounting for the positive gravity anomalies

6.4 Implications for rift dynamics

The Santos basin displays complex structure, with a number of zones containing structures of different orientations (Fig. 6.7). During early rifting, my interpretation is that the majority of these zones developed contemporaneously, at a similar time to the development of the dyke swarms onshore, and the outpouring of continental flood basalts in the Paraná basin, and the formation of the lavas which have been documented in the Santos basin (Mohriak et al., 2008). If this is the case, these structures respond in different ways to E-W extension, the NE-SW faults to the north and southeast of the basin, become wrench dominated whereas the N-S faults become extension dominated, in the centre of the basin. The extension dominated faults coincide with a negative gravity anomaly, consistent with thick sediments (Fig. 6.5d). The deepest pre-salt fault blocks are also found in this area (Fig. 6.5 b). This is consistent with regional partitioned transtension, with the majority of crustal thinning taking place in the extension dominated regions, whereas the wrench dominated regions to the north and south thin the crust less, and consequently have thinner sediment, thicker basement and higher gravity. This idea could be tested using detailed refraction seismic data for the region to map the Moho, in order to identify thickened and thinned regions.

As rifting continued, the thinned crust subsided thermally, leading to the formation of the sag horizons (Karner and Gamboa, 2007) above the Sao Paulo plateau and across much of the basin. During this period, strain apparently localised into two regions east and west of the Sao Paulo plateau, with faults continuing to be active in these regions, and cutting the base of the salt. In the centre of the basin, most of these faults trend N-S, whereas towards the eastern edge of the basin, many trend NE-SW. The western region eventually broke off from what was to become Angola, it is possible that both of these regions later became the sites of oceanic spreading centres, with spreading in the centre of the basin hypothesised by Scotchman et al(2010), among others. Faults on top of the Sao Paulo plateau and the north of the basin were at this point inactive. Evidence for erosion prior to the deposition of the salt (Fig. 6.6) suggests that some of these regions may have been sub-aerial at the time, possibly due to the Sao Paulo plateau being uplifted.

The cause of the migration of deformation away from the Sao Paulo plateau is unclear. The majority of the structures which remained active during the deposition of the salt are oriented NNE-SSE, or even N-S, perpendicular to regional extension vectors. This suggests that while the rift began partitioning into wrench and extension dominated domains, through time, wrench dominated regions became inactive, possibly due to their orientation relative to regional extension vectors making deformation difficult at lower strain rates (eg. Teyssier and Tikoff (1999), or possibly due to the cessation of dykes compensating for much of the N-S shortening which would be expected if the regions to the north of the basin were wrench dominated (See chapters 5 and 7 for full discussion of this).

Many authors have suggested that transfer zones segment the offshore basin and this study has shown little evidence to support the existence of these structures. No clear hard-linked structures can be seen, and whilst the location of zones of antithetic and synthetic faults suggests segmentation within the basin, in many cases these zones overlap, or have diffuse edges, which are inconsistent with the presence of large transfer zones.

6.5 Conclusions

Mapping of faults and the top-basement and base-salt horizons in the Santos basin shows a complex rift, with a number of domains containing faults with different orientations and presumably different kinematics. A zone of roughly N-S faults in the centre of the basin corresponds with thicker sediments and a gravity low, suggesting this deformation in this region was extension dominated. To the north and south of this region, wrench dominated zones correspond with higher gravity, possibly reflecting thicker basement as a result of wrench dominated extension. Many faults remained active during the thermal subsidence of the basin, and during the start of the deposition of the salt. These faults are located in two regions, one to the southwest of the basin and the other at its eastern edge. Both of these regions may have been coincident with the sites of ocean spreading. In the southwest of the basin, these faults trend roughly N-S, showing that extension switched from being partitioned into wrench and extension dominated domains to being purely extension dominated. The causes of this are unclear, however, data from the onshore regions has potential to shed further light on the influences on these structures.

7 Discussion and Conclusions

The various structural datasets I have collected shed light on the development of specific aspects of the SE Brazilian margin. Moreover, the combination of these datasets offers a powerful tool to study both the origin and evolution of the Santos basin, and influences on its development and that of the continental margin as a whole. The three main datasets that have been described in previous chapters comprise lineament data, which shows the geometries of large-scale structures onshore; field data, which details the kinematics of faults, fractures and dykes at small scale onshore, and their relationships to other brittle structures largely within basement rocks; and offshore seismic data, which gives information about geometries offshore, and also about timings of events. Conversely, age constraints are difficult to obtain when studying faults and fractures in basement rocks onshore, whereas kinematic and geometric relationships are not well constrained offshore. This chapter deals with the conclusions of the project as a whole. To summarise the conclusions from the previous chapters, these are:

- Lineaments form 3 regional lineament zones, consistent with the location and trend of 3 regional dyke swarms. Two of these zones can be correlated with lineaments on the African margin.
- Structures observed in the field trend parallel to major lineament trends. At outcrop, complex sets of fractures formed as a result of regional transtension. The Serra do mar and Ponta Grossa regions can be considered wrench dominated, whereas the Florianopolis region is extension dominated. Dykes commonly share geometries with fracture sets at outcrops, and in many cases, appear to have intruded along pre-existing brittle structures.
- Faults in the offshore basin fall into two distinct trends. NE-SW faults in the northwest and southeast of the basin trend parallel to structures onshore in the Serra do mar region. NNE-SSW faults in the centre of the basin trend parallel to lineaments, faults and fractures in the Florianopolis region. Some NNE-SSW faults in the centre of the basin can be seen to cut the base of the salt.

This chapter discusses the findings from the previous chapters further, and integrates the findings from the onshore field-based, remote-sensed, and offshore datasets. The conclusions of the project are highlighted, and suggestions for future work to test, and to build upon the findings of this thesis are given.

	Outcrop Data	Remote Sensing Data	Offshore Seismic
Fault Geometry	2D and 3D relationships	2D Relationships only	Large (Km+) scale relationships only
Fault Kinematics	Kinematic indicators, offset senses and amounts		
Fault Timing	Cross-cutting of structures of a known age		Relationship between faults and stratigraphy
Cross-cutting relationships	Cross-cutting relationships between faults, fractures and dykes		
Basement Fabrics	Orientation, composition, structure	Large Scale (100m+)orientation only	
Regional scale structures	Requires field exposure	Trend Only	
Igneous intrusions	Orientation, size, relationship with pre-existing structures	Trend only	
Mantle Fabrics	Possible using SKS studies		

Table 7.1 – a summary of which data are available using the three methods I have used in this thesis. Green = Data available; Yellow = available data limited; Red = method is inappropriate. Outcrop analysis offers a diverse variety of data, but identification of timings is dependent on the identification of structures of a known agt. Regional scale structures cannot be readily identified at outcrop, unless their locations are well constrained. Interpretation of remote sensing data is strongly dependent on other datasets to ground-truth ages and types of structures. Offshore data can be used to identify timings and geometries of faults, but cannot be used to interpret small scale or basement structures. 2D and 3D geometries of structures are the only features for which all methods are appropriate.

7.1 Comparison between lineament trends and field data

The onshore datasets can be readily assessed for similar orientations across the scales by comparing rose diagrams of lineament data with rose diagrams created purely from the strikes of faults, fractures and dykes collected in the field. Figure 7.1 shows rose diagrams for field data across the study area. Because of their close proximity, Caraguatauba (Ch 5.4.1.11) and Sao Sebastião (Ch 5.4.1.12) have been presented on the same diagrams. In addition, all outcrops on Florianopolis (Ch 5.6) have been grouped, as have those around Ubatuba (Ch 5.4.1.7). Figure 7.1 shows that the trends of brittle structures, especially dykes, are relatively uniform within each of the three distinct regions: Serra Do Mar, Ponta Grossa and Florianopolis (Figs. 7.1 and 7.2). The trends of these structures are parallel to both dominant and secondary lineament trends, and clearly fit into the same three regions identified during the lineament analysis (Fig 7.2, Chapter 4.3)). The key features that are consistent with lineament trends throughout these regions are the dyke orientations. Fault and fracture orientations are more variable.

This similarity between lineament orientations and the syn-rift dykes and their spatially associated faults and fractures, suggests that perhaps there are larger structures of syn-rift origin onshore. At present, to my knowledge, no published data for syn-rift faults exists in either the Florianopolis region or the Serra Do Mar region. The Ponta Grossa region, however, is known to contain syn-rift structures, as shown by Strugale et al (2007).

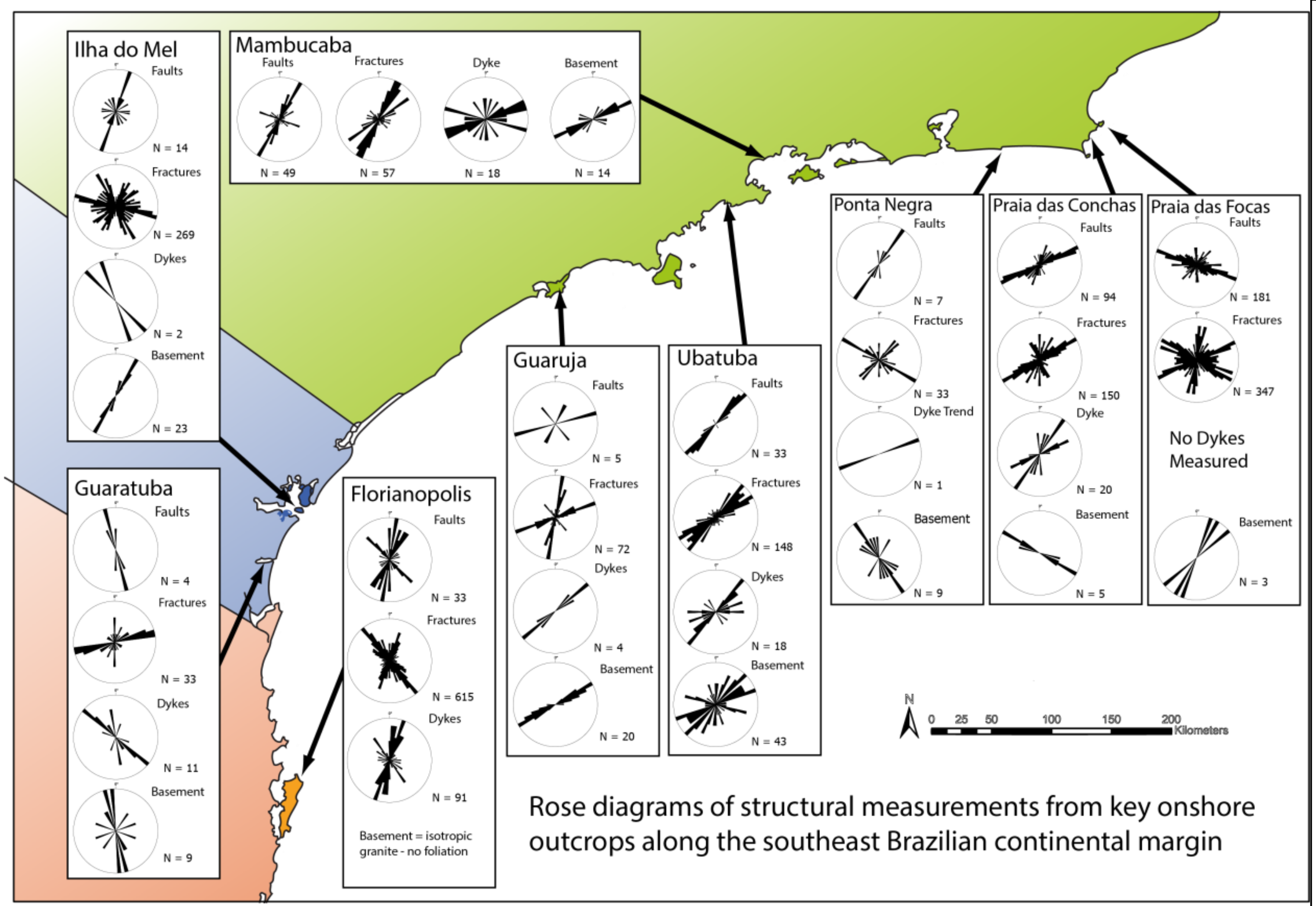


Figure 7.1. Field data presented in chapter 5 drawn as rose diagrams. The NE-SW trends in the Serra Do Mar region, NNE-SSW and NNW-SSE trends in the Florianopolis region are clear, as are the NW-SE trends of dykes and fractures in the Ponta Grossa region. Variations are seen across the area, consistent with lineament analysis, but on the whole, these structures correlate very well with lineament trends for the regions in which they are found. The Florianopolis, Ponta Grossa, and Serra do Mar Lineament domains are coloured orange, blue, and green respectively.

7.1.1 Lineaments and reactivation

Superficially, the similarity between the trends of structures observed at outcrop and the mapped lineaments supports the view that basement structures are reactivated by sub-parallel brittle structures as proposed by many authors (Franco-Magalhaes et al., 2010; Gontijo-Pascutti et al., 2010; Tello Saenz et al., 2003; Zalán and Oliveira, 2005). The field based study (Chapter 5) has, however, shown that direct reactivation of basement structures and fabrics across the area is often not present and cannot be assumed. Many outcrops show basement fabrics that are too shallowly dipping, too folded, or too mechanically strong to be reactivated. Where steeply-dipping basement is seen, reactivation is only found where that basement trends NE-SW, in the case of Mambucaba, or is strongly foliated, in the case of Ponta Negra. In other cases, such as Ilha do Mel, reactivation of basement fabrics only accommodates small amounts of deformation, whereas the more prominent, larger displacement NE-SE structures crosscut basement fabrics. Figure 7.2 shows the 3D orientation of the same structures that have been shown in Figure 7.1 plotted as poles to planes. In this figure, faults, fractures and dykes are plotted separately to show the obvious parallel alignments between the different structures. Basement fabrics, whilst appearing to trend parallel to brittle structures in Figure 7.1, are in fact generally much more shallowly dipping, highlighting the need for field-based studies to document the full 3D relationships when undertaking lineament analysis. This is an important consideration for all studies, since a number of previous studies assume reactivation based on the similarity between different trends observed in remotely sensed data (e.g. Dore et al, 1997, among others). These findings support those of Holdsworth et al. (1997).

The presence of large scale basement structures could be influential in determining the orientation of rift related structures (section 7.1). These terrane-boundary scale structures (e.g.km-scale shear zones) have been mapped onshore, but may be inaccessible or buried beneath tropical soils or rainforest, making field based study difficult or impossible (see chapter 5.4.1.6). Lineament data could potentially shed light on these structures, for example if lineament orientations can be seen to change between different terranes, or near to terrane boundaries.

My detailed lineament analysis finds little evidence for changes near to or across terrane boundaries, and suggests lineament orientations do not vary between different terranes (Figures 4.8 and 4.9). In the Serra do Mar region, where the majority of the terranes of the Ribeira belt are exposed, lineaments display a dominant NE-SW orientation both near to and away from terrane boundaries.

Structures which do not follow the NE-SW trend (such as the NW-SE trending lineaments seen in figure 4.2) cut across terrane boundaries, and therefore do not appear to have been influenced by the presence of large basement structure. The same appears to be true for lineaments in the Florianopolis and Ponta Grossa regions, where basement still trends NE-SW (whith the exception of the Florianopolis batholith, where little basement structure can be identified.

Comparisons between lineaments and field data are limited by a number of factors, including the difficulty in understanding 3D relationships between lineaments discussed above. The main issue, however, is one of scale. The lineaments are typically many kilometres long, in comparison with structures observed in the field, which have a few centimetres, if any, offset and lengths that are of the order of 100 metres or less. Lineament analysis at multiple scales has, however, shown that lineament trends picked at larger scales correspond well with those picked at smaller scales. More lineaments trending away from the dominant NE-SW trend are seen at 1:500,000 scale than at 1:3,000,000 scale (Figs 4.5, 4.6 and 4.7), and provide a better match to trends that are observed in the field, suggesting that the higher resolution lineament studies are able to pick out trends similar to that at outcrop scales. Whilst this suggests that the ‘scalability’ of geological structures may not be applicable to the largest scales, it may be related instead to data resolution and quality at the larger scales. Since the same 90m resolution hillshaded data was used for the analysis at all scales, it seems likely that smaller features that have a wider range of orientations will be visible at smaller scales. These smaller scales are the most comparable to the field data.

The scattered nature of the outcrop locations does not make for ideal comparison with lineament trends. Lineaments vary in density, with lower densities in the low lying, flat coastal areas where outcrops are most common. This leads to an issue that, whilst the lineament analysis has excellent regional coverage, outcrop data is only available in isolated exposures along the coast. Outcrops that are located large distances from one another cannot be readily compared with one another, and structures recorded at outcrop cannot be directly linked to lineaments. Despite this, the similarity between the trends observed at outcrop and the lineament analysis results suggests that these lineament trends do reflect brittle structures. It is clear that in each of the large scale lineament domains, structures at outcrop scale, whilst showing local differences, are likely to mirror lineament trends. Dykes, for example display consistent trends within the major lineament zones, as do larger faults. Fractures and smaller faults tend to have more scattered orientations, resulting from

2nd and 3rd order structures formed during regional oblique tectonics (see Chapter 5), but the principal trends still reflect the lineament zone in which they are found.

An ideal way to both improve coverage of field data, and to compare it with lineament data would be to find more field localities inland, however, exposure inland is limited, and outcrops are typically highly weathered, making structural interpretation difficult (see 'Quatis, 5.4.1.6). In addition, where the rocks are faulted and fractured, weathering (and the subsequent erosion of weathered material) tends to be much higher, due to the ease with which meteoric fluids are able to percolate into the fractured rock. This further limits outcrop. Rio de Janeiro itself is an excellent example of this, where tall, relatively unfractured rocks, such as the Sugar Loaf Mountain and Corcovado, reach heights of hundreds of metres, whist the more fractured rocks in between are much more weathered, and form less elevated regions on which much of the city is built.

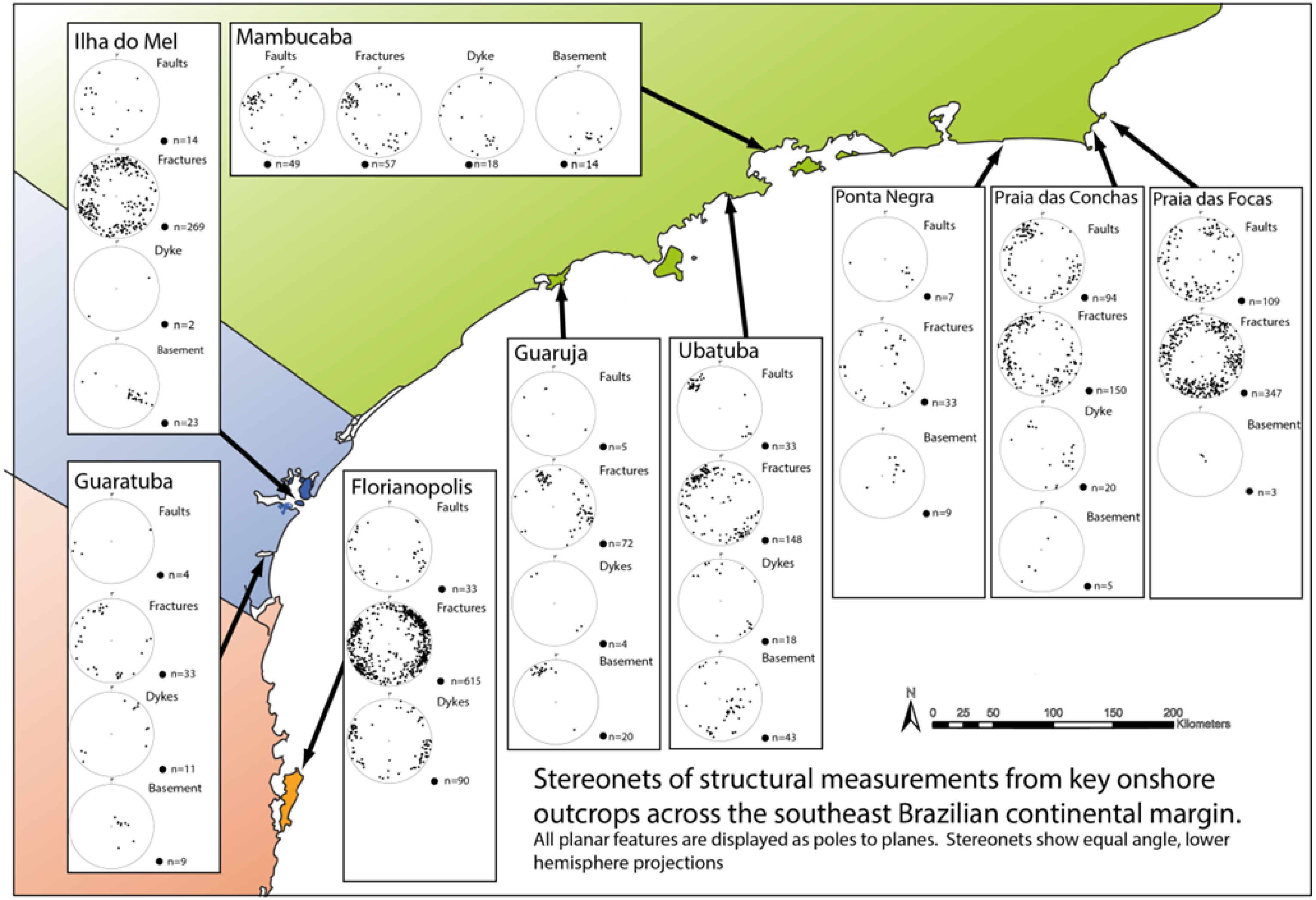


Figure 7.2 – the data seen in figure 7.1, plotted as poles to planes. The steeply dipping nature of the majority of faults and fractures is clear here, and is consistent with transtensional deformation, and also provides little evidence to support low angle normal faulting as a mechanism for rifting. Basement dips are highly variable, and are often not steep enough to be easily reactivated. The Florianopolis, Ponta Grossa, and Serra do Mar Lineament domains are coloured orange, blue, and green respectively.

7.2 Timings of onshore events

As described in chapter 5, establishing timings for onshore events is difficult. A simple time-frame, based on knowing the ages of dykes (each with diagnostic mineralogies), and cross-cutting field relationships has been utilised in this study. However, this is not specific enough to yield robust and reliable structural chronologies. It has not proved possible to assign ages to all lineaments and lineament sets, due to the difficulty in ground-truthing individual structures on such a large scale. It is therefore often unclear which events happened before during and after rifting. Since dykes commonly intrude parallel to, and in some cases, along pre-existing fractures, many of these fractures are likely to be older, or at least of a similar age to the dykes. Due to their orientation, kinematics, and the lack of previous brittle tectonic events, particularly in the Serra Do Mar and Florianopolis regions, I have concluded that many of these dyke-parallel fractures are syn-rift in origin. Many structures parallel to the dykes, such as those at Mambucaba, show conjugate geometries consistent with sinistral shear (Fig. 5.23A), showing that it is not simply those structures that are parallel to the dykes that are syn-rift in age.

In the Florianopolis region (Ch 5.6), dykes and fractures follow two main orientations (NNE-SSW and NNW-SSE) with apparent mutual crosscutting relationships, again, suggesting a similar syn-rift age. In the Ponta Grossa region (Ch 5.5), NW-SE fractures may be related to the Ponta Grossa dyke swarm, but also may be related to the development of the Ponta Grossa arch. Strugale et al. (2007), proposed that many NW-SE structures, and NE-SW structures are syn-rift (135Ma) features. They also proposed a shift in fault orientations from NW-SE during dyking to NNE-SSW later in the rift. This compares well with evidence I have collected from the Serra Do Mar region (Ch 5.4), where the earliest syn-rift faults, which influence the orientations of the dykes trend NE-SW, whereas most fractures seen cutting the dykes trend NNE-SSW.

7.3 Onshore-offshore correlations

The parallelism between structures and lineaments observed onshore and faults seen in the offshore basin are seemingly very clear (Fig. 7.4). Towards the north of the basin, faults strike parallel to structures in the Serra Do Mar region, suggesting that their orientation is similarly influenced. It is reasonable to suggest that dykes probably underlie this region offshore, as these are clearly important in the development of the NE-SW structures in the Serra Do Mar region. There is no compelling reason to believe they simply stopped intruding at the modern day shoreline. The geometries of faults seen in this region, with mostly NE-SW structures, but some small NNE-SSW structures suggests the faults here may have formed under transtension (Fig. 7.3).

Towards the centre of the offshore basin, faults trend parallel to the majority of the earlier (NNE-SSW) of the two sets of dykes seen in Florianopolis (see chapter 5.6 for discussions about timings of and relationships between dykes on Florianopolis), suggesting again that similar controls may have affected the development of both the onshore and offshore structures. Whether the Florianopolis dyke swarm extends this far beneath the offshore basin is unclear, but the lineaments seen in northern Namibia show that this same structural trend can be found on either side of the Atlantic (Fig. 7.3). The orientation of the faults and dykes on Florianopolis is consistent with a more extension-dominated origin, and the region is possibly an offshore continuation of the Florianopolis lineament domain. Whilst again, there is no reason to expect the dykes to stop at the shoreline, their extent under the Santos basin is unclear. Judging by the width of the Ponta Grossa dyke swarm (about 300km, based on the width of the lineament zone perpendicular to the trend of the dykes), it is possible that, if all rift arms are of a similar width, the Florianopolis dyke swarm underlies some of this region, but it is unlikely it underlies the full extent of it (although the Ponta Grossa region could be considered a 'failed rift', and therefore other dyke swarms may be wider).

Few structures share the orientation of the Ponta Grossa lineaments in the offshore basin, supporting the ‘triple junction’ model for the evolution of the basin, although some transfer zones, suggested by previous authors (Cobbold et al., 2001; de Souza et al., 2009), do lie in this orientation. If the transfer zone structures are ‘real’, structures in this orientation could have accommodated some of the dextral component of rifting (in the style of antithetic faults). I have found little evidence for transfer zones in the form of hard linked structures, either onshore or offshore. If the ‘triple junction model’ is correct, NW-SE structures (including dykes) should not continue into the basin. The ‘triple junction model’ (Fig. 7.3) is also supported by the fact that no simple correlation can be made between the Ponta Grossa arch and lineaments on the African margin.

A key difference between the offshore structures and those which can be seen onshore is the scale at which they are seemingly developed. Most of the offshore faults are hundreds of kilometres long and form large tilted fault blocks. Structures of this scale cannot be clearly resolved onshore, where most of the structures are of limited extent and accommodate little, if any offset. This is likely to be due to the location of the 'hinge' – the region separating the majority of rifting from the relatively undeformed hinterland (Figure 7.5). The hinge trends parallel to the coast (Zalán and Oliveira, 2005), and is likely to be controlled by the same features that controlled the development of structures onshore, such as large scale basement structures or mantle fabrics. Due to the geometric similarities between the structures observed onshore and those offshore, I propose that this hinge is likely to have developed after the formation of the dyke swarms and their associated faults and fractures, as the extension of the region increased, forming the early Santos basin. The location and orientation of the hinge could potentially be controlled by the strong structural heterogeneities formed as a result of the rift-related dyke intrusion, although this hypothesis is difficult to test using the data I have collected.

The apparent partitioning seen between the wrench-dominated domains to the north and the southeast of the basin (section 6.3.2.4), and the extension dominated region in the centre is a likely consequence of oblique tectonics (De Paola et al., 2005). In many regions where partitioned transtension is hypothesised, such as the Northumberland basin (De Paola et al., 2005), basement reactivation has been proposed to explain why structures are partitioned into wrench and extension dominated domains. If the reactivation of large, NE-SW structures is responsible for this partitioning, there should be evidence for this onshore, such as in the region between the Ponta Grossa lineament domain, and the Florianopolis domain. Whilst I have found no such evidence for this reactivation at outcrop scale, large structures are present in this area, which contains the NE-SW trending Luis Alves craton (Fig. 2.7). The presence of these large, terrane boundary scale structures could provide a mechanism for this partitioning, if they consist of structures or lithologies which are mechanically weaker than surrounding rocks.

Another hypothesis to explain this partitioning may be the presence of a distinct basement unit beneath the basin with a different composition, e.g. strongly heterogeneous or mechanically weak rocks which are easier to fault. This could explain the apparent deepening in the central basin relative to the margin to the north and west and the outer high to the south and east. This in itself would not explain why faults in the central basin do not trend parallel to structures to the north and south, since structures onshore in the Serra Do Mar region follow NE-SW trends (with an array of conjugate structures) regardless of lithology (the strongly foliated rocks at Guarujá compared with the relatively weakly foliated rocks at Praia das Focas, for example).

A third option may be the presence of NNE-SSW or N-S trending basement structures in the centre of the basin. To my knowledge, there is no evidence for any such structures, although enhanced gravity and magnetic surveys would be able to test this hypothesis. The offshore extent of the Dom Feliciano belt may underlie this part of the basin, although if the Ribeira belt correlates with lineaments in southern Angola, as lineament analysis suggests, this may not be the case, as orientations consistent with the Ribeira belt can clearly be seen in this region, as well as in the south of the basin (Fig. 7.3).

Figure 7.5 shows a section through the Ribeira belt and the Santos basin, based on my interpretation of offshore seismic data, and a cross section modified from Heilbron et al. (2008). The section shows the disparity between the steeply dipping basement of the Juiz de Fora domain (exposed inland), and the shallow dip and complex folding of the Oriental terrane, which is exposed near the coast. Zones of Westward and Eastward dipping faults can easily be identified (see figure 6.7), as can the 'outer hinge', where outboard faults can be seen to cut the base of the salt. The section also shows the separation between the available seismic data and the shoreline, both in terms of geographic distance and depth to basement. A 'hinge zone' has been added to the section to account for this separation. An important observation from this section is the apparent similarity in scale between the Eastward and Westward dipping shear zones in the Central Ribeira belt and the zones of Eastward and Westward dipping faults in the offshore basin, suggesting that basement features on 10's of km scales may have influenced the orientation of rift related structures. It is difficult to tell what is causing the apparent partitioning, especially without evidence of what basement underlies the central Santos Basin. Improved correlations between Africa and South America, based on detailed mapping of basement units on either side of the Atlantic may help by allowing a more reliable reconstruction. The best source of evidence would clearly be the analysis of basement rocks from this extension-dominated region using core samples taken from wells. This would, however, be impractical and incredibly expensive. Xenoliths within intrusions, if present could give information on basement lithology, but are unlikely to give any clear idea of the structure or orientation of basement.

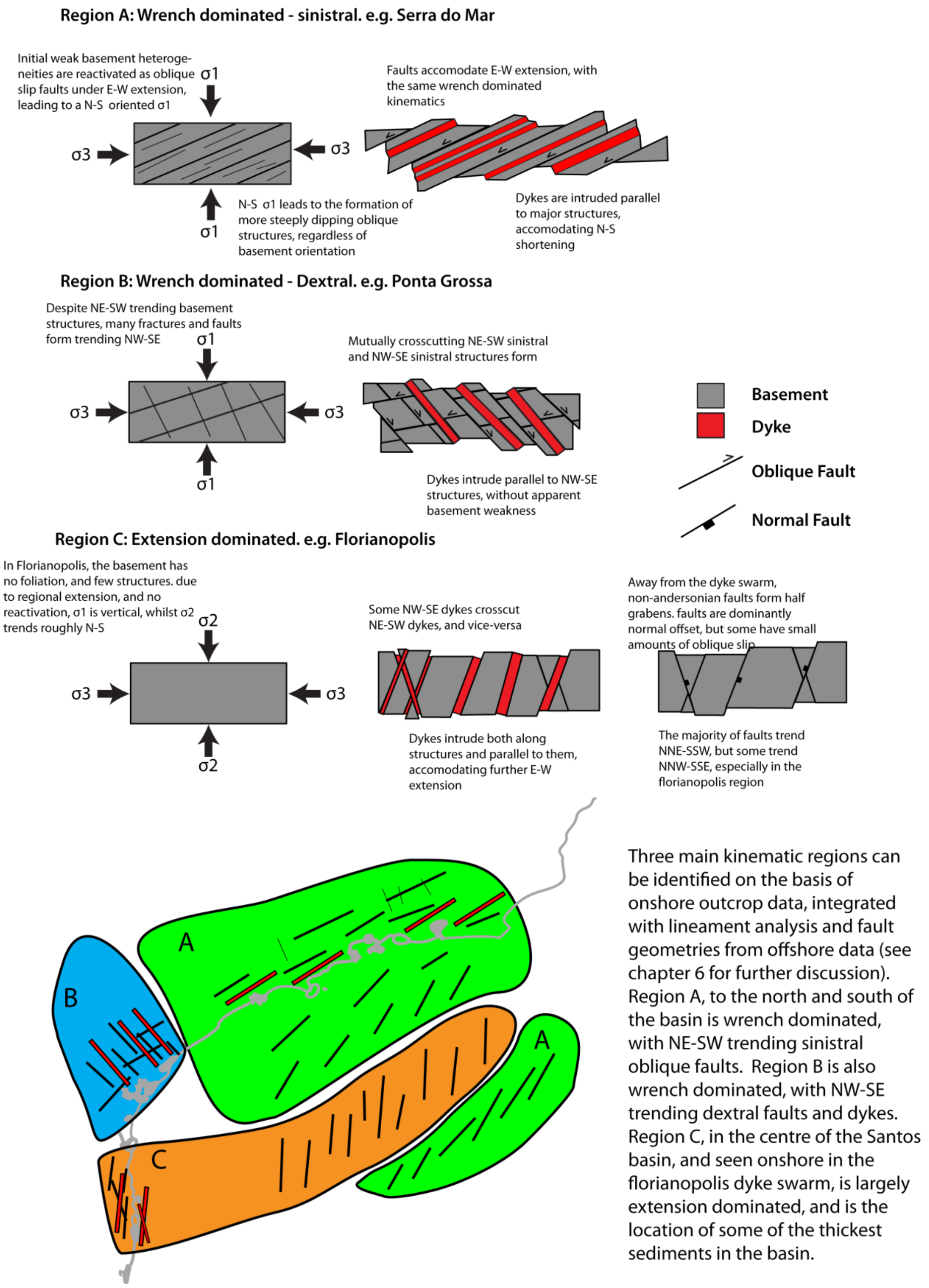


Figure 7.3. Simplified map-view (N to top of page)models for the early rift kinematics of the three main zones A, B, and C (top), and the location of these zones on and offshore (bottom), based on field and offshore data. In each zone, structures are closely parallel to dykes, but basement structures (such as shear zones or foliations) are likely to play a role in governing the overall orientation of stress axes within the region.

Faults that cut the base of the salt trend N-S in the centre of the basin (Ch 6.3.2) support the view onshore that later structures are more extension dominated, due to their higher angle relative to regional extension (and therefore higher values of α). The NE-SW structures on the outer limit of the basin show that the syn-sag deformation did activate structures trending in more oblique orientations than those N-S structures. It is unclear what caused the apparent localisation of extension in the central basin. The presence of a N-S ocean spreading centre, as hypothesised by many authors, including Scotchman et al. (2010) would explain the localised nature of the faults which cut the sag and the base of salt .

A progressive change from partitioned transtension to extension dominated deformation could explain why the N-S trending faults remained active in the central basin. As the basin extended and deformation migrated away from the hinge line, faults would be expected to be active at increasing distances from the hinge, eventually breaking up to form the south Atlantic. The NE-SW trending faults to the east of the basin would therefore be expected to have been active for longer, as deformation migrated seaward. These two separate influences could explain the pattern of later faults in the basin.

The fact that some N-S structures remain active throughout the sag, whilst NE-SW structures to the north of the basin do not, could be explained by the cessation of dyke intrusion. Whilst dykes are intruding, faults are able to deform significantly obliquely to regional extension because the dykes are accommodating much of the N-S shortening which would be expected if the region was deforming in a wrench-dominated style (eg.Teyssier and Tikoff, 1999). This N-S shortening would lead to a space problem which would either need to be solved by northwards extension within the basin, or southwards movement of the rocks to the north of the deforming region. This N-S shortening seems unlikely, as faults formed during the sag period, and those which crosscut the dykes in the field, typically trend N-S or NNE-SSW, and are therefore unlikely to have accommodated this N-S movement, considering the region would also have been extending E-W prior to breakup. If dykes were not intruding, these faults would therefore likely be unable to deform as oblique-slip faults under E-W extension, and would become inactive. NNE-SSW and N-S trending structures do not create such a space problem, and therefore are more likely to stay active, especially if influenced by an incipient ocean spreading centre.

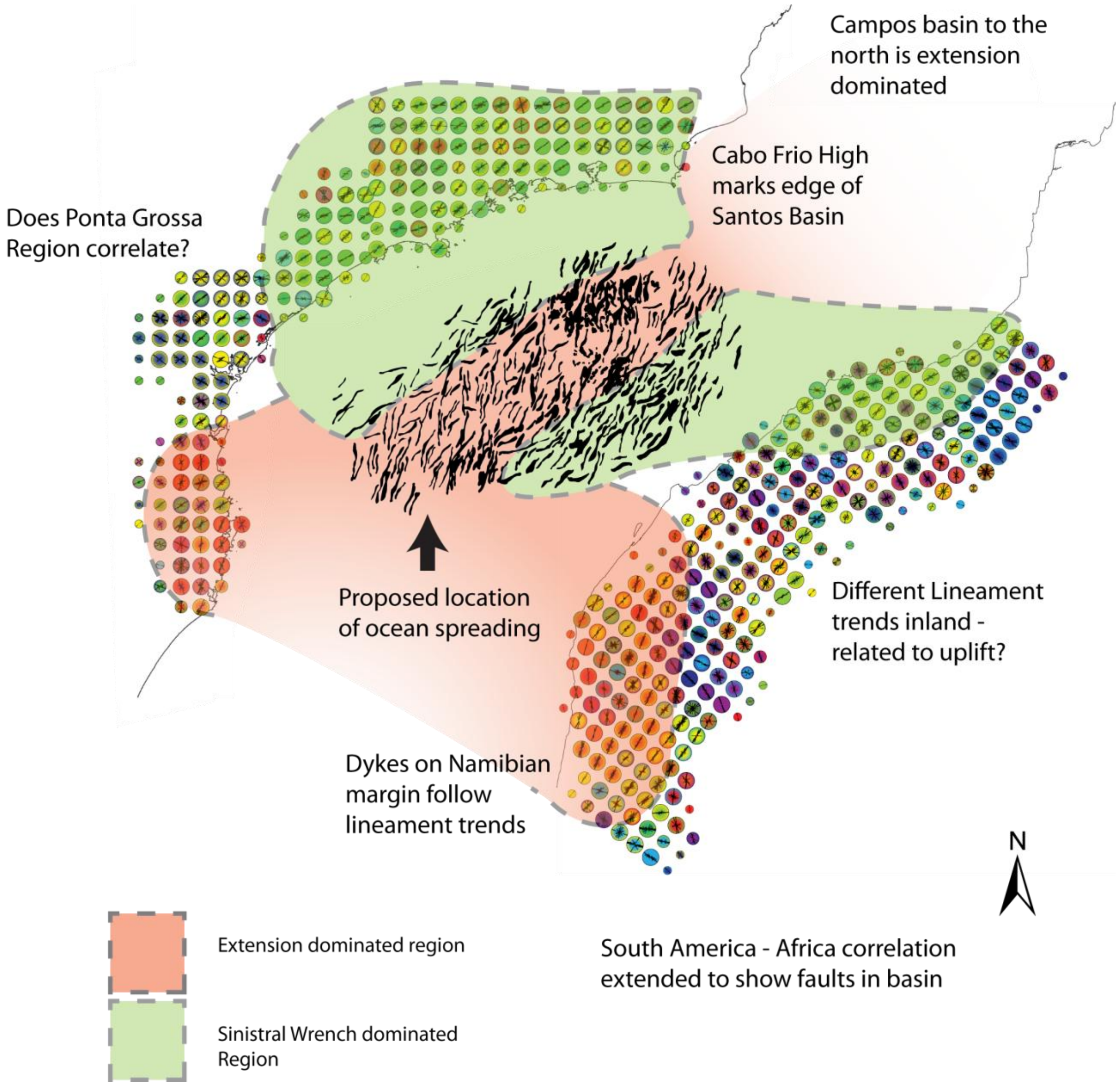


Figure 7.4. Structural domains in the Santos basin, based on lineament analysis of the conjugate south Atlantic margins, and faults in the offshore basin. To the north and south, the basin is bounded by two large oceanic lineaments; the Florianopolis lineaments and the Cabo Frio high. Whilst these divide the offshore basin, no such features are evident onshore. To the north, on the Brazilian margin, basement structures and dykes curve, trending closer to N-S. To the south, on the Namibian margin, dykes continue to trend parallel to basement. Lineament trends support correlation of the Serra Do Mar and Florianopolis regions, but not the correlation of the Ponta Grossa region.

The causes of the partitioning between the wrench and extension dominated regions are unclear. They could be related to a different basement lithology beneath the central basin, or possibly to reactivation of large basement structures.

A possible reason the basin is so wide is the localisation of significant extension following the deposition of the salt. An incipient oceanic spreading centre may be a consequence of this.

7.4 What has influenced the location and orientation of these structures?

In the offshore basin, the orientation of faults seems to be related to, and influenced by similar factors that have affected structures onshore. The similarity in geometry, particularly between structures to the north of the basin and the Serra Do Mar region, suggests that whatever has influenced the development of the onshore faults, fractures and dyke swarms, is likely to have influenced the evolution of the offshore basin.

Basement influence is one of the major models which has been proposed by a variety of authors to explain the fault orientations (Franco-Magalhaes et al., 2010; Gontijo-Pascutti et al., 2010; Tello Saenz et al., 2003; Zalán and Oliveira, 2005). Basement influence can be seen clearly at a number of outcrops, such as Guarujá and Mambucaba (Ch 5.4.1.12 & 5.4.1.5), with basement structures and fabrics reactivated by later faults, but, it cannot be seen consistently across the margin in all exposures. In addition to this locally inconsistent relationship between basement and brittle structures, a number of other problems exist with basement influence being the primary reason for rift-related structures to have formed in particular orientations. If large basement structures such as the one seen at Quatis (Ch 5.4.1.6) are obliquely reactivated under E-W extension, causing a NE-SW trending rift to develop, then strain compatibility arguments for an overall transtensional regime should indictate that faults and fractures would be expected to form more orthogonally to extension between these large reactivated structures. Given that these features are not seen in lineament analysis, or in field data (with the exception of some small scale structures at Guarujá), this model does not appear to apply to the margin.

Another reason basement influence does not appear to be the only factor affecting the orientation of structures in the area is that of the three lineament domains only two feature lineaments parallel to basement fabrics, and only one of those (the Serra Do Mar lineament zone) shows any evidence for reactivation of basement structures at outcrop. Structures in the Florianopolis region could be a result of basement reactivation, as basement structures of the Dom Feliciano belt trend NNE-SSW (Passarelli et al., 2011), although the Florianopolis batholith underlies much of the onshore extent of the lineament zone, and no structures or fabrics can be identified at outcrop scale in this region.

A larger scale control which has been proposed to explain the orientation of structures on the margin involves mantle anisotropy (e.g. Tomassi et al, 2009). These fabrics, formed during older tectonic events such as the Pan African Orogeny, are weaker in particular orientations, and can strongly influence the development of rifts. Whilst this model offers an explanation for why the rift may have been oriented NE-SW since the main orogenic belt, the

Ribeira is NE-SW trending, it does not account for the trends that define the other 2 rift arms. Furthermore, whilst there is evidence for NE-SW trending mantle fabrics beneath the Serra Do Mar, there is no such evidence under either the Florianopolis or Ponta Grossa regions. Since the Dom Feliciano belt trends NNE-SSW, it is possible that mantle fabrics beneath it do trend parallel to the belt and may have been reactivated. Whilst this model does provide a partial explanation for the general orientation of the rift, it does not provide a clear explanation for why the structures are found in their present orientation at the surface.

Several previous authors have proposed a model for the evolution of the basin involving the development of a large triple junction, either plume influenced or otherwise (Burke and Dewey, 1973; Coutinho, 2007). The observed lineament zones correspond strongly in terms of orientation and structural style with the predictions made by such a model. A number of authors (Burke and Dewey, 1973; Gallagher and Hawkesworth, 1994) have proposed that this triple junction is related to a mantle plume, which formed the flood basalts in the Paraná basin. Other authors have proposed that the uplifted regions onshore in the Serra Do Mar are also evidence for this same plume (Ribeiro, 2006; Thompson and Gibson, 1991). The general problem with this extended argument is that the uplifted regions formed several million years after the intrusion of the dykes, and are therefore perhaps unlikely to be related to the same event (Japsen et al., 2011). Similarly, other authors have suggested that the Paraná flood basalts, or the dykes are unrelated to mantle plumes (Renne et al., 1996; Rosset et al., 2007). The presence of dykes in the Serra Do Mar region that are much older than the flood basalts in the Paraná basin also suggests the dykes and associated structures may not relate to a mantle plume. There are clearly problems with applying a triple junction model to this region.

A model that best satisfies the available evidence would be to suggest, that regional-scale basement weaknesses or mantle fabrics are responsible for the orientation of the NE-SW rift arm in the Serra Do Mar. By contrast the NNE-SSW rift arm in the Florianopolis region is the result of orthogonal rifting under approximately E-W extension, whilst the Ponta Grossa arch could then either be a kinematic response to these arms developing obliquely to one another, or could have formed due to pre-existing NW-SE structures in the area, which have been proposed by previous authors. A prediction from this model is that structures in the offshore basin would likely show geometries and kinematics related to the Florianopolis and Serra Do Mar arms, rather than the Ponta Grossa rift arm, and that the Ponta Grossa arch would not correlate with Africa. My lineament and offshore studies support this interpretation.

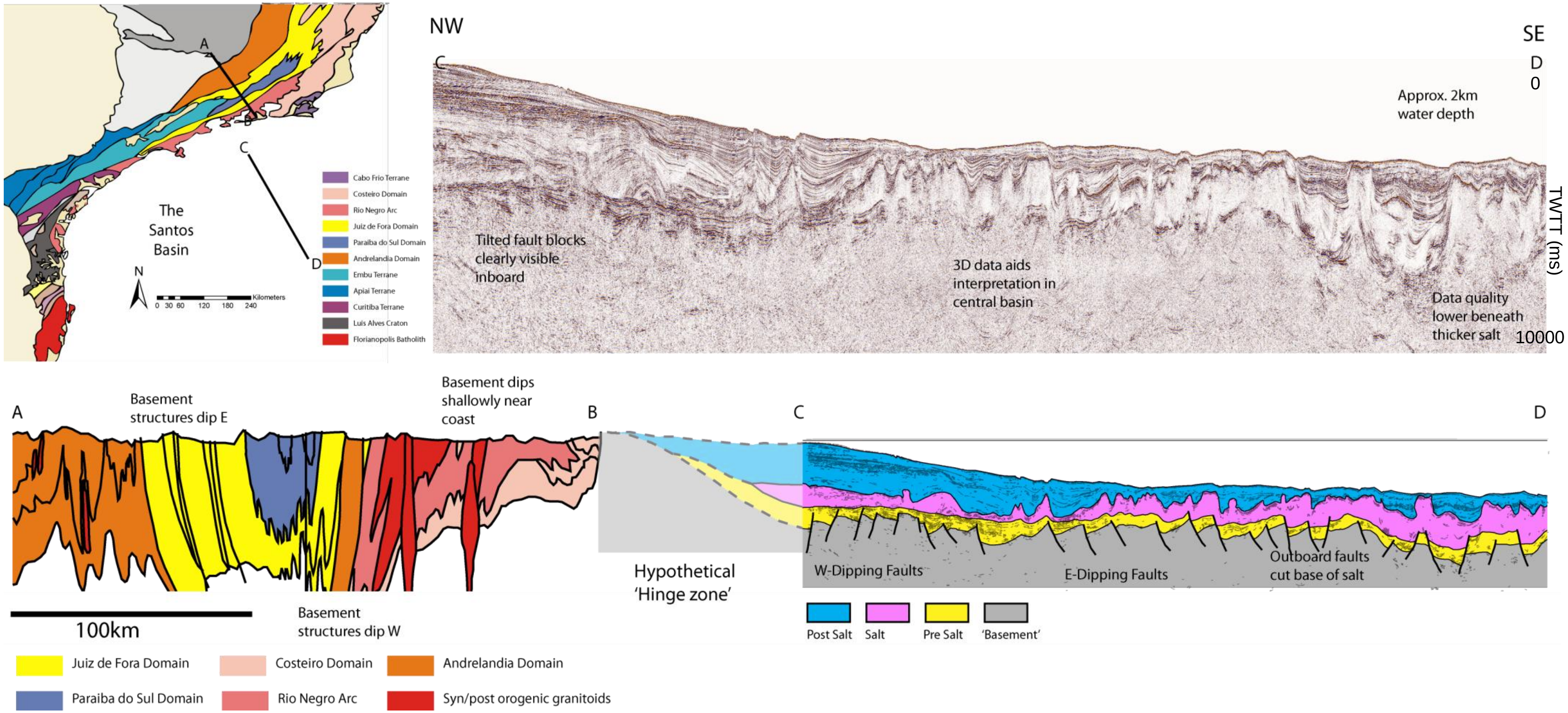


Figure 7.5 – a composite section created using seismic data from the offshore basin, and a cross section through the Ribeira belt, modified from Heilbron et al, (2008). Location map, showing the approximate locations of the seismic section, and the cross section is modified from Passarelli et al. (2011). Note: seismic line is time migrated, so vertical scales are not precise. Line location is approximate and for illustrative purposes only. Data examples courtesy of the WesternGeco/TGS Brazil Data Alliance.

7.5 Why are younger structures parallel to basement and rift related structures?

A key question concerning brittle structures onshore is why they trend NE-SW (with minor variations, and some conjugate structures) regardless of their age and origin. Lamprophyre dykes, and structures which they are related to, follow the same trends as the rift-related structures. This inability to distinguish structures of different ages is a key problem I encountered during fieldwork. A number of events have been described in the literature, with different kinematics (Ferrari, 2001; Riccomini et al., 1989). Since many structures do not appear to be influenced by local basement anisotropies, it seems unlikely that these structures would form in the same orientation regardless of their origin.

The presence of multiple orientations of slickenlines on many structures across the area confirms that many of the brittle structures have been reactivated. This reactivation could be the cause of the similarity between the trends of younger structures and those which formed during the main phase of rifting. Whilst it is impossible to say whether or not the large faults which formed the late Cretaceous and Cenozoic rift basins have reactivated older structures, this reactivation would be a compelling reason why they formed in this orientation. The influence of rift-related structures on the post-rift development of continental margins has been highlighted by Osmundsen and Redfield (2011), who show how continual reactivation of rift-related structures has controlled the location and amount of uplift of the Norwegian onshore margin. The relationship between rift-related geometries and later uplifts is not seen, however, in lineaments in Africa, where the uplifted region inland displays very different lineament geometries These geometries may have been formed during the uplift events, and if so, would be unrelated to rift-related structures.

7.6 Scientific context of the study

Literature that describes the early evolution of the Santos basin is relatively limited. Many regional studies focus on the global geodynamic implications of the rifting, and attempt to use data from the region to address problems concerning correlations with southern Africa (Aslanian et al., 2009; Torsvik et al., 2009; Unternehr et al., 1988), and the role of hyperextension in the development of a particularly wide basin (Reston, 2010; Unternehr et al., 2010). Previous studies focused onshore have concentrated largely on either the geochemistry and petrology of the dykes (Coutinho, 2008; Guedes et al., 2005), or the development of the uplifted regions, and faults which formed after the rift (Hackspacher et al., 2004;

Riccomini et al., 1989; Zalán and Oliveira, 2005). Studies published concerning the offshore basin are largely focused on the role of transfer zones in its development, and how these structures can be linked with onshore regions (de Souza et al., 2009; Meisling et al., 2001).

Of the studies concerning the onshore region, only a few deal with rift-related structures. Strugale et al (2007) show structures in the Ponta Grossa arch, which appear to change in orientation during the early stages of rifting. The observations presented by Strugale (2007) fit well with my observations of fault localisations in the offshore basin, and those NNE-SSW structures which cut the dykes in the onshore region. My interpretation of the change in fault orientation caused by the change from wrench to extension dominated transtension following the cessation of dyke intrusion; differs from the interpretation Strugale et al, who relate the change in orientation to large scale re-orientation of regional stress during rifting. Stanton et al (2010) describe dykes and faults in the Cabo Frio terrane, and their associated magnetic anomalies. They suggest that basement is not the local control on the orientation of these structures, and that deeper structures may be involved in their orientation. My study agrees with these conclusions, based on evidence from across the region.

Whilst I have found little evidence for basement reactivation across the area, many other studies (with the exception of those mentioned above) have assumed that basement reactivation is responsible for the orientation of rift related structures onshore (Franco-Magalhaes et al., 2010; Tello Saenz et al., 2003) and offshore (Meisling et al., 2001). The lack of evidence for direct reactivation at outcrop scale shows that reactivation of basement fabrics across the region cannot be assumed. The similarity in trend, however, between the NE-SW trending basement of the Ribeira belt; and the NE-SW trending faults, fractures and dykes in the Serra do mar region, and in the offshore basin; is unlikely to be coincidental. It is possible that larger, weak structures such as crustal scale shear zones may have been reactivated, and some evidence exists in the literature for this reactivation (Gontijo-Pascutti et al., 2010). Detailed study of large scale basement structures is needed in order to identify those which are weak enough to reactivate, and were in the correct orientation for reactivation, in order to identify whether large scale basement structures have been reactivated.

Previous authors (Stanton et al., 2010) have proposed that the reason for the apparent change in the kinematics of regional extension after dyke intrusion is due to the rotation of the South American plate. Whilst this is possible, the model I propose does not require this to happen. The Stanton et al, (2010) study, among others (Moulin et al., 2012) proposes that initial extension was orthogonal to the coast, rather than E-W, based on extension perpendicular to the trend of the dykes in the Serra Do Mar, and regional plate reconstructions (Moulin et al., 2012; Stanton et al., 2010). If this initial orthogonal extension is the case, it leads to complications when understanding the Florianopolis dyke swarm, which appears to have opened relatively orthogonally to E-W oriented rifting. If both extension directions were present during rifting, the western edge of the basin (e.g. the Florianopolis region) would have extended at a high angle to the extension direction to the north of the basin (the Serra Do Mar region), which is incompatible with both available evidence from the central Santos basin, and kinematic modelling of the south Atlantic opening (Nurnberg and Muller, 1991; Torsvik et al., 2009). My observations suggest that the reason the dykes are in this orientation in the Serra Do Mar region is that they follow pre-existing brittle structures. Where seen, kinematic data suggests that these structures are sinistral in the Serra do Mar region, which again, suggests initial opening was oblique, rather than orthogonal. This highlights the importance of studying structures onshore and offshore, and understanding their kinematics, especially when constructing regional kinematic and plate restoration models.

Several studies have shown that basins to the south of the Walvis ridge, for example, the Colorado basin in Argentina (e.g. Loegering et al. 2013), experienced a significant N-S extension prior to the onset of E-W Atlantic rifting. This highlights the fact that regional extension vectors are not always constant, and that assumptions of extension direction based on the trend of oceanic fracture zones may not be valid. As discussed in the previous paragraph, the field data I have collected, in particular the N-S trend of structures in the Florianopolis Domain, and the sinistral-oblique faults in the Serra do Mar Domain, do not support a margin-parallel phase of extension prior during the early phase of rifting. Furthermore, the lack of evidence for such a change in extension direction in the Kwanza basin (Angola), and in the Campos basin, suggest that an assumption of roughly E-W extension during the early evolution of the Santos basin can be considered valid. New data, such as E-W trending syn-rift dip-slip faults could, however, call this assumption into question.

Whilst few studies present field structural data as evidence for the initial opening of the south Atlantic, a number of studies have attempted to relate the uplift and cooling history of the margin to the opening of the offshore basin, using Apatite

Fission Track Analysis (AFTA) (Gallagher and Brown, 1999; Hackspacher et al., 2004). These studies have proposed multiple reactivations of brittle structures as a mechanism for variable cooling histories across the margin. These multiple reactivation events are consistent with my hypotheses concerning the close parallels between rift-related and brittle structure in the onshore regions. Field structural data for reactivation, such as faults with multiple slickenlines, or reworked fault rocks, along well defined structures would greatly strengthen the conclusions of these studies and would be greatly improved by dating of fault and fault-related mineralisation in the region.

The cause of hyperextension in the Santos basin has been the subject of a number of papers (Reston, 2010; Unternehr et al., 2010). Onshore I neither find evidence for low angle faulting or evidence for faults having been rotated to low angles and then cut by later structures. This is possibly because many of these structures are likely to be found at lower crustal levels than the outcrops seen onshore were formed at. Offshore, again, I find little evidence for these structures, although seismic imaging of the top basement horizon is poor, and structures beneath this horizon are not possible to map. The amount of basement heterogeneity seen onshore would not support a basement influenced detachment model, as there are few large structures which dip shallowly and consistently, in the onshore region. Given that the Ribeira belt formed by dextral transpression (Heilbron and Machado, 2003), this would further weaken the case for basement influenced detachment faults, because few basement structures dip shallowly, or consistently enough to be considered candidates for low angle reactivation . Low angle faults may, however, have formed as structures which cut basement fabrics. Further evidence is needed from the offshore region to test these ideas.

7.7 Conclusions

Three main structural domains exist on the onshore Brazilian margin. These domains have been defined using lineament analysis, and within each, outcrops show relatively consistent structural geometries and kinematics, regardless of the local orientation of fabrics in basement rocks at the present day ground surface. These structural domains are the locations of three major rift-related dyke swarms. The domains are: the Serra Do Mar domain to the north of the basin; the Ponta Grossa domain to the northwest of the basin, and the Florianopolis domain to the west of the basin. The Serra Do Mar and Florianopolis domains can be correlated with similar and probably equivalent lineament domains on the African margin.

Structures in these domains comprise consistently oriented dykes with parallel fractures and faults. In addition to the dyke-parallel structures, a number of other trends of fractures can be seen at all outcrops, consistent with the complex structure typical of oblique deformation. Major structures in the Serra Do Mar domain typically trend NE-SW, with an array of orientations of other structures. Major faults typically show sinistral kinematics. Dykes appear to intrude along pre-existing faults. Faults and dykes in the Ponta Grossa domain trend NW-SE, and faults typically display dextral-oblique kinematics. Secondary structures in the region trend NE-SW, parallel to the trend of the local basement structures. In the Florianopolis domain, faults and dykes form two apparently mutually cross-cutting sets, trending NNE-SSW, and NNW-SSE. The only large fault seen in this domain shows dip-slip kinematic indicators, suggesting this region deformed approximately orthogonal to E-W regional extension. The three domains together appear to form a 'triple junction', formed during E-W extension

Two main fault trends are seen in the offshore Santos basin: NE-SW faults occur in the north and southeast edges of the basin, and N-S trending faults in the centre of the basin. The similarity between the fault orientations in the offshore basin, onshore lineament orientations, and the orientations of brittle structures seen at outcrop suggests that similar influences have been responsible for the geometric development of structures onshore and offshore.

The orientations of faults in the offshore basin, when combined with data from the onshore region suggest structures in the basin are partitioned into wrench- and extension-dominated domains. During later rifting, extension dominated faults from the centre of the basin remained active, suggesting an evolution from transtensional deformation to more extensional deformation later in the rift. This change is tentatively linked to the cessation of dyke intrusion to the north of the basin, and the development of a localised spreading centre to the south of the basin.

Potential influences on the development of faults are unclear. However, a speculative model suggests that regional rift trends have been influenced by orogenic mantle fabrics formed during the amalgamation of Gondwana. Local trends do not appear to be directly controlled by basement structures (faults, fabrics, contacts etc) but the reactivation of large, weak structures could be a potential influence on the orientation of larger rift-related faults. Once these faults formed, the Serra Do Mar region is likely to have deformed by wrench-dominated transtension.

Structures which formed in this setting may trend parallel to these large structures, despite not being locally influenced by basement.

7.8 Future Work

This project has highlighted a number of key areas for future research, to test and build upon the conclusions of my work, and to further understand the evolution of the basin and the south Atlantic as a whole.

7.8.1 Continued and further field analysis

Further fieldwork on the margin would improve data coverage and help ground-truth lineament analyses. The identification of new outcrops both inland and in coastal regions would not only increase the size of the dataset, but may also help to answer key issues related to basement influence. The identification of large basement structures which have been reactivated during the rift is a priority, given that my evidence suggests that this is the most likely form of basement influence on a large scale. Particular target areas include the Central Tectonic Boundary: one of the largest basement shear zones. Clear evidence for reactivation along this structure would create a very strong case for the role of large basement structures.

Rather than studies on a regional scale, such as this one, focussed studies on particular areas have the potential for much more detailed data analysis. Lineaments can be picked from aerial photographic data, or airborne LIDAR imagery on a very small scale, again, enhancing the detail of the study. The regional geologic evolution of the Brazilian margin was a major focus of this study. As a result outcrops are scattered and lineaments are mostly picked on a large scale. Detailed fieldwork carried out on smaller study areas has the potential to answer specific questions about the relationship between basement and brittle structures, and the relationship between brittle structures themselves.

The areas between lineament zones should also be an important focus for future study. The northern limit of the Florianopolis lineament zone coincides with the south western limit of the Ribeira belt, and the location of the Luis Alves craton (Cordani et al., 2003). It may also relate to the edge of the offshore extension dominated region. Evidence for reactivation of structures here could help to explain the reason for the apparent deformation partitioning seen offshore. Field study of potential transfer zones could also test the case for these, which are some of the only structures which might be able to be correlated between the onshore and the offshore.

Whilst field data can provide additional ways to ground-truth lineament analysis, integration between lineament data and high resolution gravity and magnetic data could also help with this. Given the scarcity of accessible outcrop onshore Brazil, these surveys may offer a simpler method to ground-truth lineaments, particularly dykes.

Rift-related faults on the margin cannot easily be dated, other than by cross-cutting relationships with structures of a known age. Recent geochemical studies have shown that minerals in fault rocks can be dated, and that timings of deformation can be ascertained with relatively high degrees of accuracy. These geochemical methods, such as Re/Os dating of pyrite have the potential to improve understanding of timings of deformation in the area, allowing onshore data to be more readily intergrated with offshore data, where faults have better constrained ages. The method does, however rely on the availability of suitable material for dating to be found in fault rocks, such as pyrite or other sulphide minerals. To date, I have not seen any of these minerals present in outcrops across the study area.

7.8.2 Analysis of new offshore data

In the offshore basin, considerable interest in hydrocarbon exploration has led to the availability of more 3D seismic data and improved sub-salt imagery on 2D data. Further drilling has also improved the number of wells, and the quality of well data available to geologists within industry. This data has the potential to further understand the pre-salt stratigraphy, to more accurately map the top of the basement, and to more accurately establish the timings of events offshore. Improved mapping of faults in the basin, based on higher resolution data, and more 3D seismic surveys will improve understanding of the geometries of and relationships between some of these structures. Software such as Move could be used to reconstruct profiles and 3D volumes, to test interpretations, and to identify the timings of different events. Traptester offers the ability to accurately model fault throw profiles, which would greatly increase the accuracy of fault maps in the basin, and help to understand the kinematics of these structures.

7.8.3 Further study of the African margin

Whilst I have presented preliminary lineament data from the African margin, ideally, field and offshore data are needed to integrate the African margin with the South American dataset fully. Lineaments and other remotely sensed data could also be compared with geophysical anomalies, should these data become available. Fieldwork on the African margin, particularly in Angola is essential if findings from the onshore regions of Brazil can be correlated across the Atlantic. Dykes and faults can be readily identified using Google Earth imagery, and field-based study of these would enable the testing and ground-truthing of the models I have proposed.

Offshore data from the African margin should also be studied, and fault geometries from the early syn-rift identified. These geometries can be restored in the same way I have restored lineament geometries from African and South America. These geometries can be compared to help to understand both onshore-offshore correlations across the area, and the partitioning which is seemingly apparent in the offshore basin.

7.8.4 Other margins?

The margins of the South Atlantic commonly show triple junction type orientations of structures (Ernst et al., 2001) along their length. these triple junctions comprise rifted margins, aulacogens, such as the Benue trough (Olade, 1978), dykes trending parallel to basement in the Damara belt (Trumbull et al., 2004), among other such features. The location of these triple junctions apparently relates to changes in margin orientation. Dykes, formed contemporaneously with rifting are exposed from the Falkland islands in the south, to the northern coast of south America. These 'triple junctions' would, therefore offer an excellent target for future work, to understand how these structures are formed, and to more fully understand the breakup history of the southern Atlantic. These areas, however, are likely to share some or all of the problems encountered during this study: namely, limited outcrop, large study regions; and difficulty establishing timings of events on margins which have been tectonically active since their formation.

Other, more recent margins worldwide may show similar structures and relationships, whilst suffering less from limited exposure and timing information. The Afar triple junction, for example, is an active continental rift, which is being intruded by dykes, parallel to larger faults (Wright et al., 2006). Within the rift, structures outcrop in a variety of complex orientations, and each region is considered to have different kinematics to regions surrounding it, leading to the formation of various discrete, obliquely deforming rift segments. The wide nature of rifting in this area (Rowland et al., 2007), the presence of active faulting and intrusion, and the fact that the region forms the centre of a triple junction, could mean that Afar is an ideal modern, onshore analogue for the earliest rifting in the Santos basin. ‘Propagators’ in the Red Sea region have also been proposed as being analogous to the incipient ocean spreading which has been hypothesised in the Santos basin (Mohriak, 2011), potentially strengthening this analogy.

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